Tunable whispering gallery modes for spectroscopy and CQED experiments

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Abstract. We have tuned the whispering gallery modes of a fused silica microresonator over nearly 1 nm at 800 nm, i.e. over half of a free spectral range or the equivalent of $10^6$ linewidths of the resonator. This has been achieved by a new method based on the stretching of a two-stem microsphere. The devices described below will permit new cavity-QED experiments with this ultra high finesse optical resonator when it is desirable to optimize its coupling to emitters with given transition frequencies. The tuning capability demonstrated is compatible with both UHV and low temperature operation, which should be useful for future experiments with laser cooled atoms or single quantum dots. A general overview of the current state of the art in microspheres is given as well as a more general introduction.

1. Introduction

Optical micro-cavities have attracted much interest in the field of quantum cavity electrodynamics [1, 2] as well as in classical and nonlinear optics [3, 4, 5].

Very low mode-volume semiconductor cavities using multi-layer dielectric mirrors have been developed. Low threshold lasing [6, 7] and cavity enhanced spontaneous emission [8, 9] have been observed. Small Fabry–Perot cavities have a larger mode-volume but can achieve very high quality factors ($Q = \nu / \Delta \nu$). The strong coupling regime has been reached between single...
alkali atoms and the fundamental mode of the cavity [10, 11]. The resulting Rabi-splitting of the coupled mode [12], as well as the single atom laser action [13] have been demonstrated. More recently an atom has been trapped by a single photon in such a cavity and its motion deduced from the optical signature [10, 11].

An attractive alternative to Fabry–Perot cavities is solid dielectric microspheres having at the same time a very low modevolume and very high quality factors. Light can be trapped in so-called whispering gallery modes (WGMs) if the refractive index of the material of the sphere is larger than the one surrounding it†. Successive total internal reflections off the concave inner surface confine the light into a thin ring close to the equator. These high-$Q$ ring modes have been observed and studied extensively in droplets [15]. It was soon recognised that the field enhancement caused by the strong confinement of the light in these modes combined with their high quality factors could lead to strong cavity-QED effects. Stimulated Raman scattering, to name but one, has been observed in small $\text{CS}_2$ droplets with a threshold of just three photons per mode [5]. Whispering gallery modes have also been used to produce lasers in microdisks [16] and to enhance the spontaneous emission of quantum dots in micropillar structures [17].

However, semiconductor microdisks and pillars can only operate in the low-$Q$ regime and microdroplets suffer unfortunately from evaporation and gravitational pull. This problem has been overcome in the pioneering work of Braginsky et al. [18]. He and his co-workers realised that whispering-gallery modes in silica microspheres provide a unique combination of small mode resonators with ultra high $Q$ factors. Moreover, these spheres remain attached to a thin stem of silica and thus are easily manipulated and are easily produced in the laboratory. For microspheres ($\varnothing \simeq 40 \mu m$) the mode-volume can be exceedingly small ($V \sim 100 \mu m^3$). The electrical field for a single photon in such a mode is of the order of $10 \text{ kV m}^{-1}$. At the same time the quality factor of, e.g. silica microspheres, can be as high as $10^{10}$ with photon storage times of the order of one microsecond [19, 20]. Clearly such a system is ideally suited for the observation of nonlinear optical effects and cavity-QED experiments.

2. Whispering gallery modes in microspheres

This section gives a short overview of the general properties of whispering gallery modes (WGMs). A more detailed account of the theory of the WGMs and on experiments performed on microspheres can be found in [21, 15].

A transparent dielectric sphere can sustain WGMs if its circumference is larger than a few wavelengths. Figure 1 shows a typical single-stemmed silica microsphere produced in our laboratory. The WGMs can be understood as high angular momentum electromagnetic modes in which light propagates by repeated total internal reflection at grazing incidence on the surface with the proper phase matching condition. The modes can readily be derived from Maxwell’s equations solved in spherical coordinates. The angular dependence of the field is naturally described with spherical harmonics. The two quantum numbers $l$ and $m$ (with $m = -l, \ldots, +l$) describe the total angular momentum and its projection upon the reference axes respectively.

† WGMs were first observed in the gallery of the cupola of St Paul’s Cathedral in London, UK. A whisper spoken close to the wall can be heard all the way along the gallery, some 42 m to the other side. Lord Rayleigh was the first to identify the refocusing effect of the curved surface as the sound travels along the gallery. He also conjectured the existence of the thus called whispering gallery modes. He also suggested that such modes of the electromagnetic field could find some applications due to the extreme confinement of the field [14].
Quantum numbers $m$ of opposite sign correspond to waves propagating in opposite directions along the perimeter of the sphere. The modes offering the highest polar confinement and thus the smallest mode-volume correspond to values $|m|$ close to $l$. In the radial direction the index discontinuity creates a potential well which combines with the centrifugal barrier to form a pocket-like pseudo-potential. This effective potential approach has been analysed in detail by Nussenzveig [22]. It provides good physical insight into many properties of the WGMs which appear as quasi-bound states of light, analogous to the circular Rydberg states of alkali atoms. The radial confinement of the WGMs is characterized by the quantum number $n$, the number of antinodes of the field amplitude. The modes with $n = 1$ are the most confined in the radial direction both in terms of the mode-volume and ‘leakage’. In the geometrical optics model these modes undergo a maximum of reflections at the surface and thus have the smallest reflection angle and the lowest diffraction losses. Modes near this condition have a free spectral range $\text{FSR} \approx c/(Nl\lambda)$, where $N$ is the refractive index and $\lambda$ is the vacuum wavelength of the light. The boundary conditions imposed on the field depend on its polarization: modes with TE and TM polarization will undergo different phase-shifts upon reflection at the surface of the sphere. Two modes which differ only in polarization will exhibit resonance frequencies a substantial fraction of an FSR apart.

In short, once the polarization of the mode is assigned, WGMs are described by three integers $n$, $l$ and $m$. The mode with the longest life time and the smallest volume is $(l = l_{\text{max}}, |m| = \pm l, n = 1)$. It is confined near the bottom of the potential well, i.e. as close as possible to the sphere’s surface. It has a maximum angular momentum of $l \approx Nka \approx Nx$, with $x$ being the size parameter ($x = ka = 2\pi a/\lambda$) of a sphere of radius $a$. Its cross section is almost Gaussian both in polar and radial directions.

Light trapped in these modes can escape out of the sphere only by tunnelling across the potential barrier which extends as far as $Na$ for this state. The very short evanescent tail ($\approx \lambda/2\pi$)
of the quasi-bound state ($n \approx 1$) implies a very weak coupling to the outside medium and thus extremely high quality factors $Q = \nu / \Delta \nu$. In highly transparent media such as fused synthetic silica the diffraction losses are negligible for spheres larger than $a = 20 \mu m$. A given $Q$ value is related to an attenuation $\alpha$ by the formula $Q = 2\pi N/(0.23\alpha \lambda)$ where $\alpha$ is expressed in dB m$^{-1}$. The minimum attenuation observed in this wavelength region on silica optical fibres is about 3 dB km$^{-1}$ corresponding to $Q = 2 \times 10^{10}$. Absorption, scattering on impurities, and residual surface roughness limit the $Q$ in practice to about $3 \times 10^9$ at 780 nm [18, 19, 20] corresponding to an attenuation of 17 dB km$^{-1}$.

2.1. Coupling light into whispering gallery modes

The very high diffraction-limited $Q$ of the fundamental modes of larger spheres implies that free space coupling to the microspheres is very inefficient. In order to achieve efficient coupling the free space beam has to be matched to the WGM. Close to the surface of the sphere the excitation beam has to have the same shape and angular momentum (with respect to the centre of the sphere) as the mode. The potential barrier created by the index discontinuity at the surface of the sphere confines almost all of the field to the inside of the sphere. However, a short evanescent tail of the electro-magnetic field protrudes from the sphere. If a material of high refractive index is brought into this evanescent wave some of the light will tunnel across the gap between the material and the sphere, also known as frustrated total internal reflection. This can be achieved with a prism of high refractive index ($N_p$) almost in contact with the sphere. If an incident beam hits the prism surface with an angle $\theta$ close to the critical angle $\theta = \arcsin(N/N_p)$ so that its angular momentum with respect to the centre of the sphere is $N_pka \sin \theta \approx Nka$ its light can be fed into a WGM. By slightly changing the angle of incidence and the frequency of the beam different WGMs can be selectively excited†. Using the prism coupling scheme efficiencies exceeding 30% can be achieved for various mode geometries. The resonances appear as dips in the intensity of the beam reflected from the prism (figure 2). The depth of these dips is a direct measure of the coupling efficiency. Due to the nature of evanescent waves the coupling rate

† This method has also been used in the pioneering work of Braginsky et al [18] and in another geometry in Paris [19] where eroded fibre couplers and tapered fibres have also been used [23].

Figure 2. Approaching a high refractive index prism to the sphere (not to scale) one can frustrate the total internal reflection of the WGMs within the sphere and couple light into or out of the sphere.
decreases exponentially with increasing gap size. The ability to control the coupling rates is an important advantage of microspheres as compared to other resonators where the coupling rate is fixed by the reflectivity of the mirrors. The highest coupling efficiency between the free space modes and the WGMs is achieved with a gap of a few hundred nanometres where the coupling rate matches the other losses of the resonator (generally absorption and diffraction by surface roughness). The intrinsic quality factors of up to $10^{10}$ can only be measured with very large gaps (typically of the order of 1 µm).

3. Experiments on microspheres in Paris

3.1. Experimental set-up

The experiments described here are all based on the prism coupler method: the light is coupled into and out of the sphere via a prism. As described above the incoming beam has to match the whispering gallery mode in frequency, spot size and angular momentum. It is therefore necessary to have full control over all parameters of the incoming Gaussian beam: frequency, waist diameter and position, and angles of incidence with the prism. Figure 3 shows a schematic of the set-up used in the experiments presented here. A photographic image of the coupling lenses and the prism can be seen in figure 4.

When narrow linewidth is required, e.g. for a measurement of the ultimate $Q$, a grating stabilized laser was used. A laser diode (Yokogawa YL78XNL) with integrated Bragg grating serves when a large tuning range is needed. A wavemeter laser provides the absolute frequency scale with a precision of about $10^{-4}$ nm. A small fraction of the laser light (~3%) traverses a calibrated high-finesse Fabry–Perot cavity. The transmission peaks of the Fabry–Perot cavity are recorded together with any absorption data taken and thus give a precise relative frequency

![Figure 3. Diagram of the experimental set-up. An 800 nm diode laser is coupled into an optical fibre and launched onto the prism and thus coupled to the sphere (both not to scale). The light emitted by the sphere under the influence of the pump beam can be monitored by photo diode and analysed by a monochromator.](http://www.njp.org/)

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Figure 4. A photograph of the central part of the experiment. The brass holder (top left of the picture) holds a single-stemmed Er$^{3+}$ doped ZBLAN sphere ($\odot = 140 \mu m$). An aspherical lens (lower right side) projects the light (10 mW, 800 nm) from an optical fibre onto the prism. Part of the laser light is absorbed by the microsphere and re-emitted at 550 nm. Some of the fluorescent light exiting the sphere can be seen in the photo as a bright spot near the corner of the prism. The lens (top right side) collimates the remaining IR pump radiation and the emitted green laser light. It can thus be analysed outside of the temperature controlled central part of the experiment.

scale. The remainder of the light couples into a single mode fibre after intensity and polarization control. This fibre leads into a temperature controlled box containing the launching and collection optics as well as the microsphere with the necessary mechanical controls. A high aperture lens collimates the light exiting the fibre onto the equilateral coupling prism (SF11). The angles of incidence and the numerical aperture are calculated in advance as a function of the size of the sphere and accordingly adjusted before introducing the microsphere. The light coupled out of the sphere is collimated and analysed outside the confinement. The microsphere itself is mounted on 3D micrometer translation stages. The gap between the sphere and the prism can be adjusted with nanometric precision using a low voltage piezostack.
3.2. Tuning microspheres

Until recently the main disadvantage of the solid microspheres has been that the frequencies of the resonances are not tunable. The free spectral range (FSR) in small spheres is of the order of THz whilst the line width of the resonances is about 300 kHz. Therefore accidental coincidences between an atomic line and the fundamental transverse whispering gallery mode are extremely rare. We have recently demonstrated a tuning device capable of spanning up to an FSR. This opens a whole new range of experiments on solid dielectric microspheres. Now fixed dipoles can be brought into interaction with these resonators. Applications include CQED experiments with cooled atoms, or cavity-ring-down spectroscopy of environmentally important gases. Recently the first practical tuning device has been developed in our laboratory [24].

A number of conditions have to be fulfilled in order for the tuning device to be useful: first of all it must safeguard the high quality factor and function for small spheres to take advantage of the reduced mode-volume. The tuning range should be of the same order of magnitude as the free spectral range (FSR) in order to be able to tune a desired WGM into resonance with, e.g., an atomic transition or resonances in quantum dots. The device has to be exceedingly stable. A change by only $10^{-7}$ of the desired tuning range would already shift the WGMs by one resonant linewidth. Good access to the sphere must be safeguarded in order to be able to approach a prism from one side and the sample the sphere is to interact with from the other. Furthermore the device should be readily producible and affordable, which is especially important for potential applications, e.g. as trace gas detectors. In many cases vacuum compatibility and/or low temperature operation would be highly desirable. Here we present two devices which fulfil all these conditions—the first is for spectroscopic applications, while the second is suited to the more demanding CQED experiments. Some details as to the production will be given and some examples of level (anti-) crossings will be presented.

In principle there are two methods to tune whispering gallery modes in solid dielectric microspheres: temperature [25] and strain [26]. At first order, both affect the mode resonance through the simple relation: \( \frac{\Delta \nu}{\nu} = -\frac{\Delta a}{a} - \frac{\Delta N}{N} \), where \( a \) is the radius of the sphere and \( N \) its refractive index. The temperature dependence of the modes is about $-2.5$ GHz K$^{-1}$. Given a free spectral range of about 1 THz for a microsphere of 60 \( \mu \)m diameter this can only serve as fine tuning. On the other hand silica glasses can be deformed elastically up to a few per cent. One FSR tuning is equivalent to $\Delta \nu/\nu \simeq 1/l$ where \( l \) is the longitudinal quantum number. For a typical sphere this implies that an equatorial deformation of 0.2\% is sufficient, which can be achieved in silica [27]. The first demonstration of strain tuning used piezodriven pliers in order to compress the microsphere [26]. About one quarter of the sphere protruded from the device, thus allowing coupling to the WGMs. For a sphere of a diameter of 160 \( \mu \)m tuning over 150 GHz at 800 nm has been demonstrated. However, the jaws restrict the access to the sphere and the device cannot be applied to spheres smaller than about 100 \( \mu \)m. This precludes its use in experiments on, e.g., quantum dots (access) and thresholdless lasing in Nd doped silica (size).

A new method has been developed recently in our laboratory in which the strain is applied to the sphere by stretching it [24]. We are now able to produce spheres with two stems, one on each pole. The strain on the microsphere can therefore now be exerted simply by pulling on the ends of the two stems. The requirements on the symmetry are rather stringent though: upon pulling the two stems even a slight angle between the two results in very large forces between the sphere and the stems and thus to early breakage.
3.3. The production of tunable silica microspheres

The starting material for the microspheres is a rod of synthetic silica glass. This is heated in an oxygen–propane torch and rapidly pulled into a fibre of 20–60 µm diameter. The sphere is created again by heating part of the fibre upon which the surface tension pulls the molten material into an approximately spherical shape. An industrial 10 W CO₂ laser serves as a highly controllable clean source of heat. The process is controlled by eye through a binocular microscope. The focusing lenses and the glass fibre itself are mounted on micrometer controlled 3D translation stages.

A lens (f = 25 mm) focuses the vertical 3 mm diameter CO₂ laser beam to a waist of about 30 µm. It thus creates a strong vertical gradient in the intensity of the infrared radiation. The fibre hanging down is only heated near the focus. The glow of the silica due to the heating is visible in a stereo microscope and serves as an indication of the temperature of the glass. (Grey and UV filters have to be used to protect the eyes.) Close to the melting point the surface tension starts to pull the glass into a round shape. However, since the laser light comes from below, the lower part of this shape will cast a shadow upon its upper part. As a consequence not a sphere but a pear-shaped object is being formed. This can be corrected for by slowly lowering the sphere past the focus of the CO₂ laser towards the region of maximum curvature of the wave-front. Thus the laser illuminates a larger region of the sphere. The resulting microsphere is symmetrical with respect to the equatorial plane. (See left-hand side of figure 5.) The production of such a sphere including the fibre preparation takes only about ten to twenty minutes on a well adjusted laser set-up.

As mentioned above it is absolutely crucial to preserve the symmetry of revolution of the microsphere and stems. Otherwise the stems will rupture prematurely. Our production set-up obeys this symmetry: the CO₂ laser beam and the fibre are both strictly vertical. However, once the melting process has started the slightest current of air will move the lower stem to one side.

**Figure 5.** The first tuning device. Two brass jaws hold a double-stemmed sphere of a diameter between 60 and 200 µm. The WGMs of the sphere can be tuned by stretching it using a fine screw and a low voltage PZT stack. The right-hand side of the figure shows a CCD camera microscope image of a typical microsphere.
In order to guarantee the fibre being vertical we thus use a small weight (5–10 mg) attached to its lower end. The focus of the laser is well above the weight, which is therefore not heated substantially. Furthermore the strong convergence of the beam ensures that the weight does not create a shadow on the sphere itself. Additionally before producing the actual sphere residual tension in the fibre, caused e.g. by imperfect mounting, is removed by annealing it with the CO$_2$ laser: close to but below the melting point the residual stress relaxes on a time scale of a few seconds.

3.4. The first tuning device

Figure 5 shows the first tuning device. The sphere with its two stems is glued between two brass arms which can be opened and closed with fine screws and a low voltage PZT stack. At the tips of the two arms are U-shaped notches of dimensions $0.1 \times 0.5 \times 5$ mm with a $3–5$ mm gap between them. Into these the stems of the sphere are fixed using standard cyanoacrylate glue. The set-screw is then tightened to remove the inevitable slack in the stems so that the PZT can exert strain on the stems and thus the sphere. Spheres with a diameter down to about $60 \mu$m and a stem diameter of about $40 \mu$m can be easily used in this device. Much thinner stems break too easily in the gluing and pre-tightening stage. The maximal travel of the piezostack is $7 \mu$m, which translates into an unloaded movement of about $80 \mu$m at the fibre. This device thus allows us to stretch the fibre by about one per cent which is close to the maximum elastic deformation tolerated by the silica glass and near the value needed to tune one free spectral range.

![Figure 6](http://www.njp.org/) A series of scans of the WGM resonances in a sphere against the voltage applied on the PZT. The horizontal axis is the frequency of the diode laser. The vertical axis shows the transmission (in arbitrary units) offset by the voltage of the PZT. A dip in the transmission equates to an absorption by a whispering gallery mode. The inset shows the closest point of the avoided crossing between the TE and TM modes. The intrinsic quality factor of the sphere was $Q = 5 \times 10^8$ (see footnote on next page).
The average tuning range of the modes has been assessed in a sphere of 210 µm diameter by continuously increasing the voltage at the PZT and observing the modes passing through the frequency window scanned by the diode laser. Assuming there is no strong nonlinearity in the tuning rate, the average tuning range of the modes with respect to the voltage applied to the PZT can thus be deduced. We measured a maximal continuous tuning range of 150 GHz, which is about half of an FSR for the 210 µm sphere studied here. A full FSR could not be reached, mainly due to the stem being significantly thinner than the sphere. Assuming a diameter of the sphere twice as large as the one of the stem the stress on the material will be four times as large on the stem. This leads to a failure before the maximum tuning range for the sphere is reached. However, the tuning range of 150 GHz, half of an FSR, demonstrated here already suffices since it requires on average only two attempts to find a sphere with predefined transverse and radial quantum numbers to coincide with a given frequency, e.g. of an atomic line.

We show in figure 6 the frequency shift upon stretching for a set of TE and TM modes. As expected, both from theory and earlier experiments [26], the two modes increase in frequency with increasing strain. The observed slopes are due mainly to the geometric deformation of the sphere. The anisotropic modification of the refractive index explains why TM modes tune more efficiently than TE modes. Figure 6 also shows clearly an avoided crossing between the two modes. For the purpose of demonstration, figure 6 shows a particularly large avoided crossing of 300 MHz due to an impurity introduced in the sphere. This greatly enhances birefringent coupling between modes of great spatial overlap but differing polarization. The splitting, i.e. the coupling of the TE and TM modes, is about 300 MHz whereas the under-coupled linewidth of the resonance is about 300 kHz ($Q = 5 \times 10^8$). Normally, i.e. when the sphere is made from pure silica only, the coupling between modes is of the order of a few hundred kilohertz.

In all other spheres produced by this method that we have tested we measured a quality factor of the order of $10^9$. These are amongst the highest at this wavelength. Figure 7 shows one such measurement on a TE mode. The linewidth of 370 kHz measured at 800 nm corresponds to a $Q$ in excess of $10^9$. As often observed in very high $Q$ spheres, the WGM resonance is a doublet. The splitting of 539 kHz between the peaks results from a coupling of modes of opposite sense of rotation due to backscattering of the light by defects in the silica or residual surface roughness [28]. As expected, the splitting remains constant even if the frequencies of the modes are tuned by stretching the sphere.

We also tested whether the strain produced by this device remained stable. The long-term stability of the modes was found to be excellent: over a number of days the modes drifted by less than 10 GHz. On a shorter time scale, the stability was limited by fluctuations in the background temperature. The quality factor can be preserved under atmospheric conditions for a few days. A reduction in the $Q$ is usually sudden and can often be traced back to a microscopic dust particle settling in the vicinity of the WGM.

† At a $Q$ of $5 \times 10^8$ the linewidth is 600 kHz. In figure 6 the width of the scan is 6 GHz. Thus these resonances are difficult to visualize. We therefore chose the gap between the sphere and the prism to be very small. This increases the coupling between the WGMs and the prism and thus enlarges the linewidth of the modes beyond their intrinsic line width (by a factor of 500 in the case of figure 6). The corresponding loss in the amplitude of the signal can easily be tolerated. The splitting between the modes at the avoided crossing remains unaffected by by the increased coupling between the free-space modes and the WGMs.

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Figure 7. The intensity of the light absorbed by the sphere. The black line is a fit of two Lorentzian lines to the data. The lines are 370 kHz wide equating to a quality factor in excess of $10^9$. The doublet originates in a coupling of counter-propagating modes due to backscattering [28].

To summarize, this first device can tune WGMs of the microspheres of down to a diameter of $60 \mu m$ by about half of an FSR whilst preserving very good access and maintaining their high a quality factor of more than $10^9$.

3.5. The second tuning device

For cavity quantum electronics experiments it is highly desirable to use very small spheres in ultra high vacuum conditions. This is difficult to realise with the first design due to the minimum size of the spheres of about $60 \mu m$. The second tuning device we developed addresses this concern. It can be seen in figure 8. It consists of a U-shaped base which can be opened and closed with a screw and a vacuum compatible low voltage PZT stack. Rods of pure silica are fixed onto the jaws of the device and subsequently bent in an oxygen–propane flame to meet at the centre in front of the device. The tips are then ground to the shape of a pyramid with a tip to tip distance of about $400 \mu m$.

Next the CO$_2$ laser is used to weld a short piece of silica fibre across the gap between the tips of the pyramids. The inevitable residual stress is removed by again gently heating the material with the CO$_2$ laser. The fibre is then placed into the focus of two exactly counter-propagating laser beams (lenses $f = 25.4$ cm). The material is carefully heated whilst the tension on the PZT is continuously increased. This stretches the material at the focus of the laser. The procedure is repeated some tens of micrometres below. The result is a double neck in the fibre. The centre between the two indentations is then heated strongly and the voltage slowly relaxed. The surface tension pulls the material thus provided into a good approximation of a sphere. (See inset in figure 8.) The relatively thick stem assures that much of the deformation results in strain on the sphere and does not just stretch the stems. The indentations on either side of the sphere reduce its ellipticity.

The second device was studied with a narrow linewidth tunable DBR diode laser (Yokogawa YL78XNL). By scanning simultaneously the laser current and the injection current into the Bragg grating this laser can be tuned continuously by up to 1 nm. Its linewidth is about 1 MHz. The tuning of the WGMs could therefore be observed directly over its maximum range. Figure 9
Figure 8. The second tuning device. On the left of the device can be seen an optical microscope image of the double stemmed ‘sphere’.

Figure 9. Frequency shift for a TM (■) and a TE (○) mode followed continuously over the maximum tuning range.

shows the tuning of two WGMs in the sphere against the voltage applied on the PZT. The frequency of the resonance was changed by 405 GHz before the device failed due to a fracture at the joint between the fibre and the mount. Half of an FSR of the sphere has thus been scanned. Again, as expected, the TE mode moved more slowly with the PZT voltage than the TM mode.

The $Q$ factor was lower than $10^9$, the value measured with the first device. This is probably due to some contamination of the sphere’s surface, possibly due to the deposition of a small amount of crystallized silica. This will be avoided in the future by a slight modification in the fabrication process.
The stability of the frequency of the modes is of particular concern for any future experiments with tunable microspheres. The tuning was found to be perfectly reversible: on a time scale of up to a week no drift of the modes, e.g. due to plastic deformation of the sphere, could be observed.

In summary, the second device can tune the WGMs by about one half of an FSR. Good access is still granted. Spheres of a diameter down to about 30 µm can be used.

3.6. A comparison between the two devices

The two different models of tuning devices presented above serve quite different applications. The first one is clearly more suitable for applications such as spectroscopy or spectral filtering. It is very simple to produce: a new resonator can readily be made and coupled to a laser in less than one hour. It might even be possible to mechanize such a production by adapting well-established pipette-pulling technology. The tuning device affords excellent access, good robustness, and ease of use. Its main limitations are its minimum sphere diameter of 60 µm and the relatively long stems necessary to fix the sphere to the jaws of the device.

The second design has a potentially larger tuning range. It permits smaller spheres to be used. Tuning of spheres down to less than 40 µm has been demonstrated. It has excellent vacuum compatibility and is more compact, thus limiting the cost of the vacuum system. Its main drawback compared to the first device lies in the more complicated production procedures requiring considerably more skill and time. The second device is being used in ongoing CQED experiments in our group.

4. Conclusion

A more detailed analysis has been reported of two novel devices for microspheres which finally allows these extraordinary resonators to be tuned into resonance with atomic and molecular transitions. This opens the way toward a whole new range of experiments in CQED and ultra sensitive spectroscopy. It has now become feasible to couple ultra cold atoms or quantum dots to the microspheres. The tunable microspheres will serve as affordable ‘super’ cavities for the detection of trace gases, e.g. by cavity ring down spectroscopy.

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