Spherical Microresonators Coated with a High Refractive Index Coating for Different Applications

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Abstract— We will discuss several applications of the coating of silica microspheres. Silica microspheres fall in the group of so called whispering gallery mode (WGM) resonators. They are known to have a very high Q-factor and a low modal volume. Therefore they are suitable for a number of different applications such as lasing, frequency comb generation or sensing. In this paper we will discuss three different applications. Firstly we will discuss the sensing properties of the coated microsphere. We have found that a high refractive index coating can greatly improve the sensing properties of a silica microresonator, improving the theoretical sensing sensitivity from 5 nm/RIU for a blank silica sphere to a maximum of 145 nm/RIU for an amorphous silicon coating. We will also discuss some experimental results dealing with the coating of silica microspheres with a LPCVD a : Si coating. Second application which we will discuss is lasing and optical amplification. By coating the microsphere using an optically active material, microsized lasers can be produced. We have coated a silica microsphere using an erbium doped glass ($70SiO_2$-$30HfO_2$) and have shown that such a system exhibits lasing. Finally we will discuss the possibility to tailor the modal dispersion of the resonator by applying a high refractive index coating on top of the microsphere. This can be a crucial step for improving the applicability of the microsphere in non-linear optics applications, such as for four-wave mixing. We used erbium doped silica hafnia glass as a probe to study the influence of the coating on the modal dispersion inside the microresonator and have found that the coating can be used to tailor the modal dispersion in a very wide range in both the normal and anomalous regime.

1. INTRODUCTION

Optical microresonators are high quality optical resonators of μmeter dimensions. Of the many different kinds of resonators the simplest one is a silica microsphere. It can be made by melting the tip of a standard optical fiber. Upon melting, the surface tension will form a high quality silica sphere on top of the fiber. This kind of silica microresonator can exhibit very high Q-factors (10^7 up to 10^9), Q-factor defined as the average number of round trips a photon can take inside a resonator before being absorbed or scattered. Inside the microresonators the light is confined by total internal reflection, so that the light is travelling along the circumference of the resonator. The modes of such resonators are called whispering gallery modes (WGM). In addition to the high quality factors the WGMs also have a very low mode volume which means that we can confine light in a very small volume for a long period of time. This makes them very useful for different applications such as sensing, lasers and amplifiers, optoelectronic oscillators or non-linear optics. The applicability of the microspheres can be further enhanced by applying a coating on the surface of microresonator. The coating can be used to functionalize the surface of the sphere, to activate the sphere or to alter the WGM confinement. In this paper we will review some of the different effects a high refractive index coating can have upon a microsphere, in particular in respect to the tailoring of the modal dispersion of the sphere, to the enhancement of the sensing sensitivity of the sphere and to the production of microlasers [1–3].

2. EXPERIMENTAL

The microspheres were produced by melting the tip of a standard optical telecommunications fiber. The typical diameter of the microspheres was found to be around 150 μm. Two different techniques have been used to coat the sphere with a high refractive index layer. The first method consist of coating a sphere with a silica-hafnia thin film using a sol-gel route. The sphere was coated with a film of the composition $70SiO_2$-$30HfO_2$ activated with 0.3% mol Er^{3+}. The films were coated using a dip coating technique. The sol was prepared by mixing a solution of $Si(OC_2H_5)_4$ (TEOS), HCl, H_2O, CH_3CH_2OH (ethanol) and $HfOCl_2$. The molar ratio between TEOS, water and the catalyst (HCl) was $n(H_2O) : n(Si(OC_2H_5)_4) : n(HCl) = 200{:}100{:}1$. The molar ratio between the TEOS and $HfOCl_2$ was chosen to be $n(Si(OC_2H_5)_4) : n(HfOCl_2) = 70 : 30$ on the basis of previous experiments. The overall amount of Si and Hf in the sol was controlled so that $c(Si(OC_2H_5)_4) + c(HfOCl_2) = 4.48\ 10^{-4}$ mol/mL in order to have a sol viscosity which makes the dipping rate 30 nm/dip. $Er(NO_3)_3 \times 5H_2O$ was added to activate the film so that the molar concentration of Er^{3+} in the sol is 0.3% mol. The mixture of TEOS, HCl and H_2O was prehydrolised at 65 °C for 1 hour before adding the $HfOCl_2$ and the Er $(NO_3)_3 \times 5H_2O$. The entire mixture was then stirred for 16 h until the sol became transparent. The dipping speed was 40 mm/min and the dipping time 20 s. After each dip the microspheres were densified at 900°C for 50 s and after every 10 dips an additional densification was made for 2 min. At the end of the deposition a final densification for 5 min at 900°C was made [4]. The second method consists in coating a sphere with an amorphous silicon coating using the LPCVD (Low Pressure Chemical Vapor Deposition) method. The precursor gas was 26% silane (SiH_4) diluted in argon. The silane flow was about 150 sccm resulting in the chamber working pressure of about 0.2 mbar. The reaction used to deposit silicon was the thermal pyrolysis of silane: SiH_4->Si+$4H_2$. This reaction is known to produce amorphous silicon at temperatures below 580°C and polycrystalline silicon at temperatures above 580°C. In our work we chose the temperature of 570°C as the deposition temperature in order to obtain amorphous silicon. The reason that a : Si is preferred over crystalline silicon when coating the sphere is its lower surface roughness which is needed in order to preserve the high Q-factor of the sphere. All the measurement of the optical properties of the spheres was done using a microsphere-taper coupling setup to couple light in and/or out of the sphere. To measure the Q-factor of the spheres a C-band tunable laser was used to sweep across the resonance. To measure the erbium emission in erbium doped coatings the sphere was excited using a 1480 nm laser. The emission signal was detected by a Anritsu MS9710B optical spectrum analyzer (OSA).

3. RESULTS

The microsphere themselves present a high quality optical resonator. If an optically active material is present inside this resonator and pumped to achieve population inversion the sphere can exhibit lasing provided the round trip gain is higher than the round trip loss. We have measured the lasing spectrum of a $70SiO_2$-$30HfO_2$ coated microsphere doped with 0.3% mol Er^{3+}. The sphere was excited using a 1480 nm pump laser. The laser was coupled into the sphere using a halftaper. The same taper was used to collect the luminescence and/or lasing signal from the modes which are counter propagating in respect to the pump laser.

In Figure 1 are shown typical lasing and luminescence spectra of a coated microsphere. In the left part of Figure 1 is the luminescence spectrum taken when the pump power was kept below the lasing threshold. We can see that the quasy-equidistant modes are visible, corresponding to different values of l. In fact, two different families of modes are visible, corresponding to the TE and TM modes. Upon increasing the pump intensity above the lasing threshold strong lasing can be observed as is shown in the right part of Figure 1. Usually the lasing is multimode, the modes corresponding to modes which are present in the luminescence spectrum as can be seen in the inset of Figure 1. Peak laser powers are around 300 nW.

Evanescent field sensing is a method which uses the evanescent field of an electromagnetic wave confined in a photonic structure (a resonator or a waveguide) to detect the presence of an analyte on the surface of the structure. A photonic structure that has been widely used for evanescent field sensing is the whispering gallery mode (WGM) microresonator [5, 6]. In this case the sensing is done by monitoring the shift of the mode eigenfrequency (wavelength) of the mode. This can be done by sweeping a tunable laser across a resonance and monitoring the shift of the resonance upon contamination of the resonator surface with an analyte. The problem with WGM sensing is that the light is confined inside the microresonator by total internal reflection and hence the evanescent tail

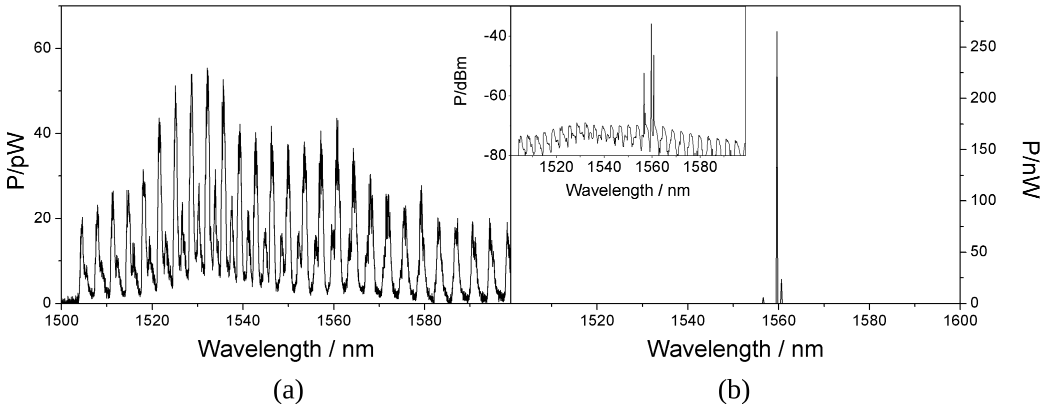

Figure 1: (a) The luminescenceand (b) the lasing spectrum of an erbium doped microsphere. In the inset is the lasing spectrum in logarithmic scale.

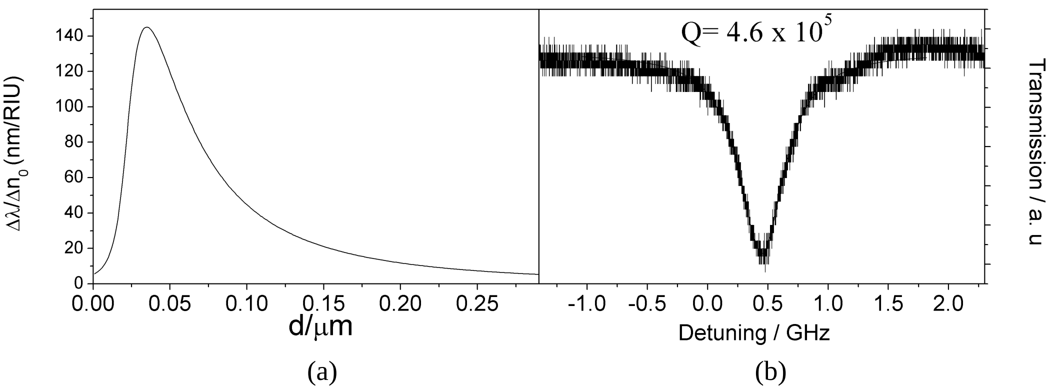

Figure 2: The sensing sensitivity vs. the coating thickness for (a) an a : Si coated microsphere and (b) the measured Q factor for a LPCVD a : Si coated microresonator, all at 1550 nm.

extending outside of the resonator is very short leading to low sensing sensitivity. If we introduce a high refractive index coating on the surface of a WGM resonator we can produce a structure which has both WGM and wave guiding properties and can have much higher sensing sensitivities than an uncoated sphere [7]. In the left part of Figure 2 is shown the theoretical calculation of the effect an amorphous silicon coating can have on the sensing sensitivity of a microsphere. The calculation shows the shift of the mode per change of the refractive index of the surrounding medium in which the sphere is located. This refractive index change is caused by the adsorption of analyte on the surface of the sphere. We can see that by choosing an appropriate coating thickness we can increase the sensing sensitivity from 5 nm/RIU in the case of an uncoated sphere to 145 nm/RIU in the case of a 35 nm a : Si coating.

In order to fully benefit from such a large increase of the sensitivity we have to make sure that the coating procedure does not degrade the Q-factor of the sphere. The coating process will necessarily introduce some scattering losses both on the sphere-coating and coating-air interfaces which could reduce the spheres Q-factor. To avoid this we must choose a coating material and procedure that allows the deposition of a highly smooth and homogenous coating. Furthermore the coating needs to be homogeneous also on the macroscopic scale meaning that the coating thickness has to be the same on all sides of the sphere. One of the few methods that allow this is the LPCVD (Low Pressure Chemical Vapor Deposition) method. Since, unlike other CVD methods, this method is not a direct flow deposition, the resulting films are highly homogenous. We have performed the coating of a 140 μm silica sphere with amorphous silicon using the LPCVD method. The Q-factor measurements of a coated sphere were made by sweeping a tunable laser across a resonance. The wavelength of the resonance divided by the transmission dip corresponding to the resonance is just the Q factor. A typical Q-factor measurement for a 150 nm coating is given in the right side of Figure 2. The measured Q-factor was 4.6×10^5. A typical value of a blank silica microspheres

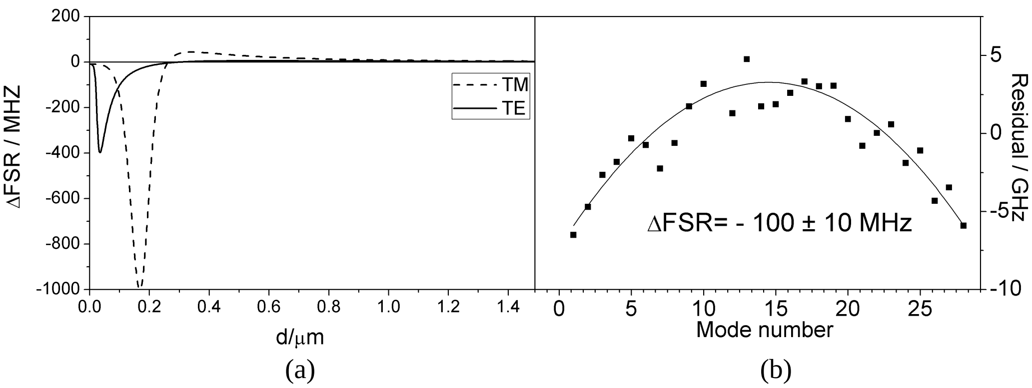

Figure 3: The sensing sensitivity vs. the coating thickness for (a) an a : Si coated microsphere and (b) the measured Q factor for a LPCVD a : Si coated microresonator, all at 1550 nm.

Q-factor is usually between 5×10^6–2×10^7. We can see that even a very thick coating (150 nm) reduced the Q factor by only one order of magnitude. This makes amorphous LPCVD silicon a very promising candidate for sensing application.

A high refractive index can also be used to increase the applicability of the sphere for non-linear optics application [1]. In particular, a sphere can be coated using a material with a different refractive index in order to change its modal free spectral range (FSR) and/or modal dispersion (ΔFSR — mode to mode change of the FSR). This argument is very important for all non-linear optics applications where small anomalous dispersion is crucial, in particular frequency comb generation using four wave mixing. In fact, to achieve efficient frequency comb generation it is vital that the modes be as equidistant as possible which requires near-zero modal dispersion. In Figure 3 is shown the calculated geometrical cavity dispersion for an a : Si coating. We can see that by choosing an appropriate coating thickness we can tailor the modal dispersion in a very wide range, both in the anomalous and normal regimes. In particular, for the TE modes the dispersion can be tailored from −400 MHz normal to 6 MHz anomalous and for the TM modes from −1000 MHz normal to 50 MHz anomalous dispersion. Furthermore they both can have zero dispersion for a specific value of the coating thickness, namely 300 nm for the TE and 260 nm for the TM modes. We conclude that this method can give us a great degree of liberty in choosing a suitable geometrical cavity dispersion. For nonlinear optics application the most suitable geometrical cavity dispersion is, of course, equal in magnitude and opposite in sign to the material dispersion which depends on the materials used.

4. CONCLUSION

In conclusion we can state that a high refractive index coating can greatly increase the applicability of microresonators in a number of applications. The coating can be used to introduce optically active materials on the surface of the sphere for production of microlasers. Furthermore the coating can be used to greatly increase the sensing sensitivity of the microspheres. And finally the coating can be used to tailor the geometrical cavity dispersion of the resonator for application in non-linear optics.

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