An Experimental Investigation of Whispering Gallery Mode Microsphere Resonators for Sensing, Lasing, and Nonlinear Optical Applications

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***Abstract* - Microsphere resonators are gaining popularity as a key component in photonic circuit devices, optical communications, sensing, lasing, and nonlinear optical applications. As one of the essential categories of optical microcavities, microsphere resonators based on whispering gallery modes (WGMs) have benefits of ultra-high Q factor, small mode volume, ease of fabrication, and low cost. In this paper, we will present experimental results achieved by our group in regards to different application of microsphere resonators:**

1) **We studied the refractometric gas sensing sensitivity and the effect of thickness of the sol-gel silica layer coated to the microsphere to detect small traces of ammonia.**

2) **Rare earth doped microsphere resonators are promising candidates for lasing applications. Tellurite, fluoride, phosphate, and silicate glasses are good hosts for doping with rare earth elements for broadband applications. Tellurite doping with various rare earth elements can provide a wide stimulated emission cross section in the communication band.**

3) **High Q factor and low mode volume of WGM microresonators is a perfect host for non-linear optics application. We will present some non-linear effects which are present in silica spherical microresonators which include stimulated Raman scattering and frequency comb generation via degenerative four wave mixing.**

Keywords* - *Whispering gallery mode, Microsphere, Microlaser

I. Introduction

Acoustical whispering gallery modes (WGMs) were first investigated by Lord Rayleigh in the dome of St Paul's cathedral in London [1]. Analogous optical WGMS have been found in micrometer sized spheres where light is spatially confined inside the microspheres surface by total internal reflection. Whispering gallery mode microresonators exhibit different geometries such as micropillars, toroids, spheres, disks and rings [2]. Among them, optical microspheres are the prime focus of several theoretical and experimental studies. Microsphere resonators acquired considerable attention due to their potential to become vital components in photonic devices, telecommunications, sensing, lasing and non-linear optical applications. Whispering gallery mode microspheres have unique properties such as a high-quality factor and a low mode volume, which make them an indispensable tool in various optical systems. Three indices, *p*, *l*, and *m*, which represent the mode orders in radial, azimuthal, and axial directions, respectively, define microresonators. Microsphere resonators can be fabricated using a variety of techniques. Melting the tip of a standard optical fiber is the most common and easiest method for the fabrication of microspheres. In our work we prepared microspheres using a commercial fiber splicer, plasma torch and micro heater method.

We mainly focused on the experimental investigation of microsphere resonators for sensing, lasing, and nonlinear optical applications. Initially, we studied the refractometric gas sensing sensitivity and effect of thickness of sol gel silica layer coated to the microsphere to detect small traces of ammonia. Silica microspheres were produced by melting the tip of a standard silica fiber using an electric arc from a commercial fiber splicer. The sol-gel method is employed to produce a porous silica layer, which is then dip coated onto the sphere. A gas molecule that diffused into the porous silica layer and interacted with the coating's whispering gallery mode changed the coating's refractive index, which induced a shift in wavelength. This mechanism is called refractometric sensing [3]. For ammonia gas sensing measurements, a signal from a tunable laser is coupled to the coated microsphere using a tapered optical fiber.

Furthermore, our work based on rare earth doped microsphere resonators for lasing applications. Tellurite, fluoride, phosphate, and silicate glasses are good hosts for doping with rare earth elements for broadband applications. The high refractive index and wide-range transparency tellurite glass offers in the communication band make it a viable material for the fabrication of microlasers. Rare earth metals including erbium, thulium, holmium, and ytterbium attracted a lot of attention because of their powerful, and broad stimulated emission cross section in the tellurite host and are therefore frequently utilized in laser systems [4-7]. Tellurite glasses exhibit exceptional mechanical and thermal characteristics as well as excellent transparency from the visible to the mid-infrared spectrum. The plasma torch method is used for the fabrication of erbium doped tellurite microspheres. We worked on erbium doped tellurite microresonators and used pump laser of wavelength 980 nm to achieve laser emission at 1562.5 nm.

In addition, we also worked on non-linear effects which are present in silica spherical microresonators. The first frequency comb generation from a microresonator is reported by P. Del'Haye [8]. We achieved stimulated Raman scattering and frequency comb generation via degenerative four wave mixing.

II. EXPERIMENTAL

For gas sensing application, silica microsphere is produced by melting the tip of a standard silica fiber using an electric arc from a commercial fiber splicer. The fabricated microsphere is coated with a porous silica layer using the dip coating method. The coating solution is made using a standard sol gel technique. Tetraethyl orthosilicate (TEOS), distilled water, and HCl diluted in ethanol are mixed together to form the sol gel solution (procedure explained in detail [3]). Fig.1 depicts the sketch of a porous silica coated microsphere. Thickness and refractive index of the coating is estimated using ellipsometry.

Signal from a tunable laser is used for the gas sensing measurement which is coupled to the microsphere using a tapered fiber. The coupled microsphere system is placed in an isolated chamber. To remove the humidity, the chamber is flushed with argon before the measurements. Fig.2 represents the set up for gas sensing measurement. Ammonia in argon atmosphere is used for sensing. Two mass flow controllers control the concentration of Ar and ammonia in the chamber. The tunable laser is swept through a small wavelength range. The transmission is

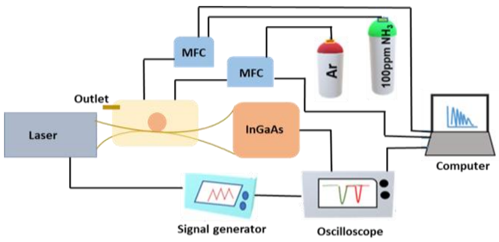

Figure 2. Experimental set up for ammonia gas sensing.

detected using an InGaAs detector (Thorlabs DET08CFC/M) which is connected to the oscilloscope.

Fig.3 depicts the schematic diagram of the plasma torch method for the fabrication of tellurite glass microspheres. To fabricate microlasers erbium doped tellurite glass is used. We used $15Na_2O_25WO_360TeO_2$ glass powder doped with 0.5 mol% Er^{3+} for the fabrication of microspheres. Plasma torch method is used to fabricate the microsphere. In the plasma torch method two electrodes are connected to a high voltage supply.

When the glass grains are passing through the electric arc from the plasma torch they melt and then acquire a spherical shape due to surface tension. Fabricated microsphere is glued to a fiber. A pump is coupled to the microsphere using a half taper. Fig. 4 shows the experimental set up for the microlaser experiment. An optical spectrum analyzer receives the counter propagating light from the microsphere. A pump laser of 980 nm is used to achieve the laser emission.

For the non-linear optical measurement, a tunable laser is connected to an erbium doped fiber amplifier which is connected to the coupled microsphere system. A tapered fiber is used for the coupling. Typical experimental set up for the nonlinear optical application used on a silica microsphere is shown in Fig.5 Signal from the microsphere is sent to the optical spectrum analyzer and an InGaAs detector using a 50:50 splitter. Output of the InGaAs detector is connected to an oscilloscope. Several non-linear effects were observed including Raman scattering and four wave mixing.

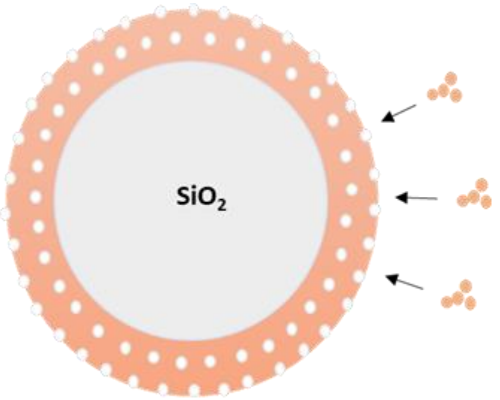

Figure 1. Sketch of microsphere coated with a porous silica layer.

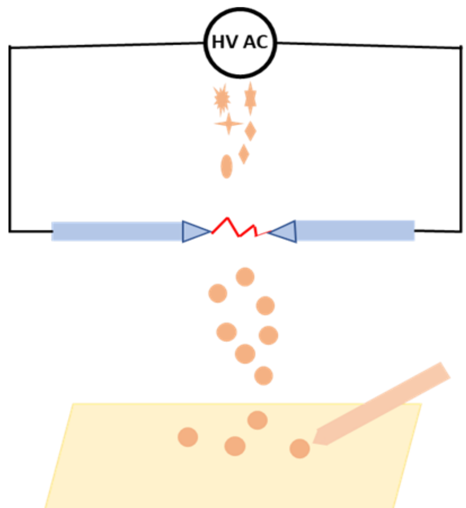

Figure 3. Plasma torch method for the fabrication of microspheres.

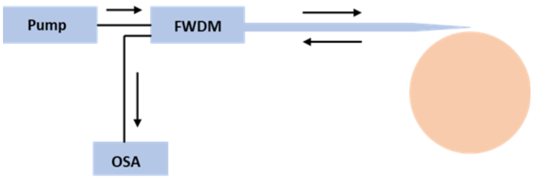

Figure 4. Experimental set up for the microlaser experiment.

III. Results and Discussions

Sensing measurements were carried out for different cycles of ammonia ranging from 1 ppm to 5ppm (Fig. 6). We found that higher ammonia concentration in the chamber leads to a higher mode shift. According to Fig. 7 the sensitivity of our system is 113.2 pm/ppm, although for higher concentrations we observe some saturation. This is because while increasing the concentration of ammonia in the chamber all the bonding sites for ammonia bonding in the sol-gel coating is occupied. The sensitivity of different modes is found to be different. Fig. 8 depicts two modes that are shifting their positions due to different sensitivities. The different modes have different sensitivity because they have different radial orders (*p* values). The major problem we faced using our set up is the difficulty for selecting the mode with desired values of *p*. (detailed explanation is given in [3,9])

Fig. 9 shows the observed erbium emission at 1562.5 nm of an erbium doped tellurite microsphere doped with Er^{3+} ions. In order to get lasing at 1562.5 nm we adjusted the coupling point between the sphere and the half taper. We used a half-tapered fiber for the coupling of 980 nm pump light into the microsphere and observed single mode lasing. The Q factor of the sphere is also measured and it is found to be 10^6. Fig. 10 shows the Lorenz fitting of the peak for the Q factor measurements.

In Fig. 11 is shown the observed stimulated Raman scattering achieved using a pump laser at 1570 nm. The Raman lines are observed at 1692 nm and 1702.4 nm. The peak at 1692 is stronger than the pump laser peak. The conversion of energy from pump to Raman line is efficient. The Raman line shift itself is between 459 and 495 cm^{-1}, which corresponds to the energies of Raman transitions in quartz glass.

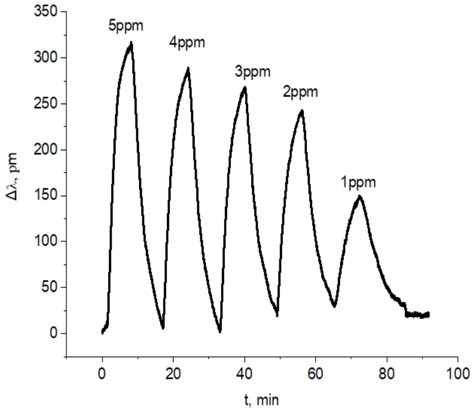

Figure 6. Resonance shift with time.

In Fig. 12 is shown a typical frequency comb extending from 1550 to 1750 nm including 46 lines. The initial 1560 nm pump serves as a seed from which different comb lines are generated. Two pump photons generate one signal and one idler photon by degenerative four wave mixing. All the other lines are then generated by non-degenerative four wave mixing between photons belonging to different lines. The lines correspond to the whispering gallery modes with subsequent *l* values. Energy and momentum conservation laws are satisfied in four wave mixing which means the comb lines have to be uniform. The lines are generated at the exact eigen frequencies of the whispering gallery modes. The Q-factors of the WGMs are extremely high so the eigen-modes must also be uniform. The uniformity of

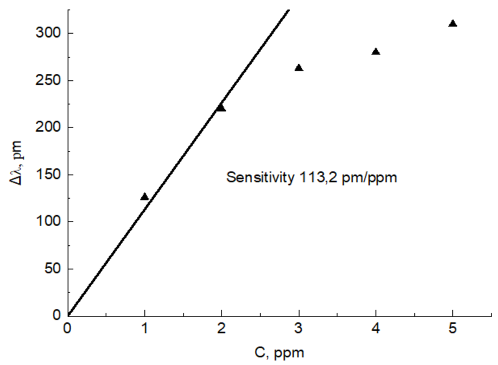

Figure 7. Resonance shift with concentration of ammonia.

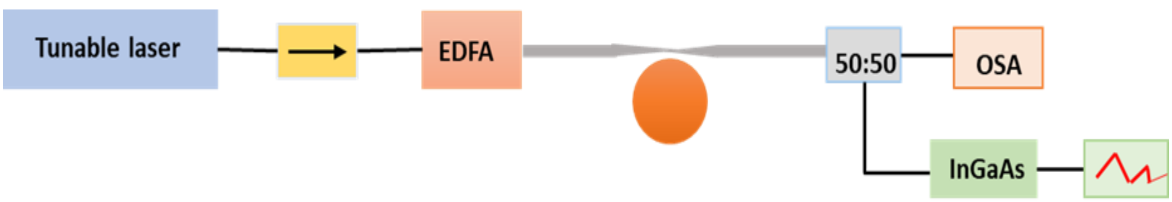

Figure 5. Experimental set up of nonlinear optical application.

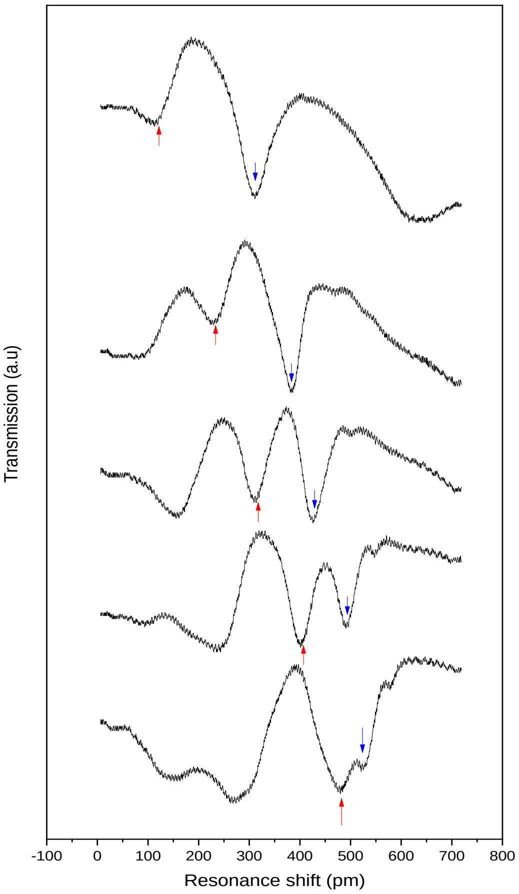

Figure 8. Transmittance of a sphere coated with a porous silica layer after the injection of 5ppm of NH_3 in the testing chamber.

the eigenmodes is determined by the dispersion of the resonator's material as well as the geometrical cavity dispersion of the sphere itself [10]. Additionally, Stimulated Raman scattering lines can also serve as an additional seed for the frequency comb.

IV. CONCLUSION

To conclude, an experimental study was made of the refractometric gas sensing sensitivities of a silica microsphere coated with a thick porous silica layer. We deduce from the observations that different modes can have various sensitivities for a given sphere and explain this by the fact that the observed whispering gallery modes had different *p* values. We demonstrated erbium doped tellurite microsphere as microlaser and achieved laser emission at 1562.5 nm. Furthermore, we observed several

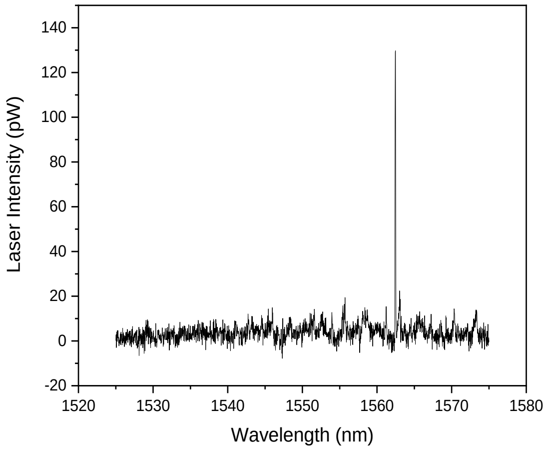

Figure 9. Laser emission of Er3+ doped tellurite microsphere at 1562.5 nm using 980 nm pump.

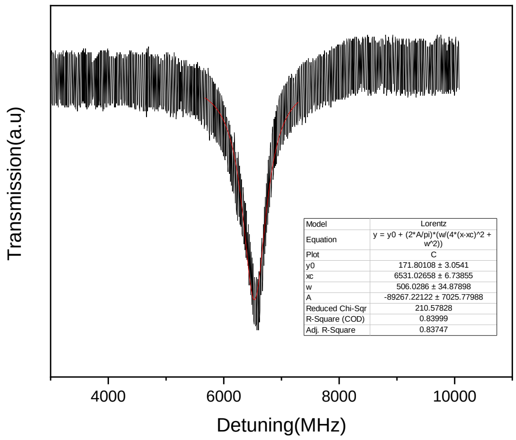

Figure 10. Transmittance of a sphere coated with a porous silica layer after the injection of 5ppm of NH_3 in the testing chamber.

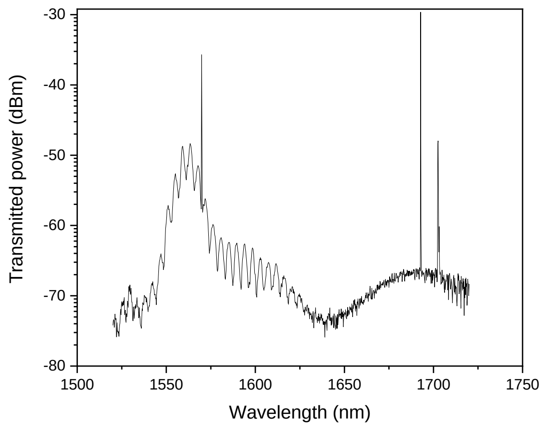

Figure 11. Stimulated Raman scattering.

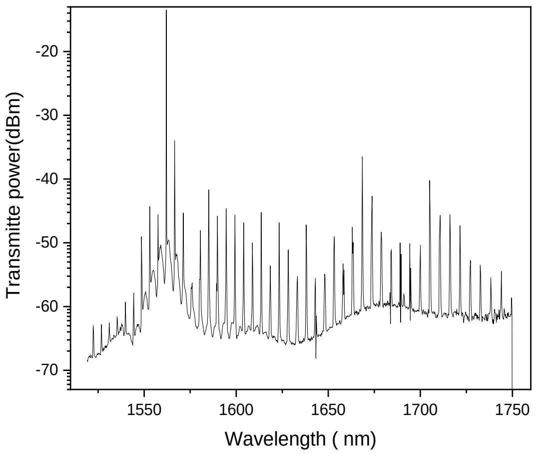

Figure 12. Frequency comb generation.

non-linear effects includes stimulated Raman scattering and frequency comb generation in a silica microsphere.

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