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By

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Introduction

Whispering Gallery modes (WGMs) in dielectric micro-cavities are resonant electromagnetic modes that are of considerable current interest because of their extremely high Q values leading to long photon residence times and very small mode volumes at optical frequencies. The wavelength locations of these resonant modes are extremely sensitive to the changes in refractive index, size as well as interactions on the surface of the micro-cavity. These properties make WGMs a good choice for bio-sensing [1- 4]. The high Q factor is also advantageous for making micro-cavity lasers [1, 2, 5]. The frequency specific WGM resonators can be used in optical switching, ultra-narrow filtering techniques [1, 5], etc. Fig 1 shows WGM in a circular dielectric structure. The figure 1 a) represents the WGM in ray optics diagram and Fig 1 b) shows the intensity distribution for an equatorial mode.

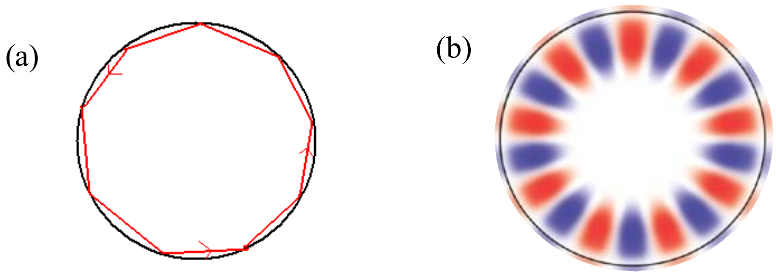


Figure 1: WGM in a circular structure. a) Ray optics representation, b) Intensity distribution.
[Adopted and modified from *Nature Photonics* 3, 15 - 16 (2009)]

The WGMs can be observed in different resonator geometries (figure 2). Commonly used geometries include micro-sphere, micro-disk, micro-toroid, micro-bottle, micro-ring, micro-cylinder, etc.

Figure 2: Microcavity - Different Geometries [2, 6]

Among the different geometries of resonators used for WGMs, the most commonly used are microspheres as they are easy to prepare and have high Q values (~10^9) [7].

The WGMs can be theoretically explained using Mie theory [8] which using Maxwell's equations gives the solution for scattering of electromagnetic radiation by a sphere. Mie theory can be used to calculate the scattering cross-section, absorption cross-section, extinction cross-section etc.

The WGMs can be characterized by three mode numbers and two polarizations. The mode numbers are *radial mode number(n)* which can take values n = 1, 2, 3,…., *it* gives the number of maxima in the radial electromagnetic field distribution; the a*ngular or polar mode number(l)* which can take values *from* 0 to n-1 and represents the extent of field in the angular direction; and the *azimuthal mode number(m)* which describes the number of maxima in the field intensity at the equatorial plane when one makes a complete rotation in the azimuthal direction. It can take values, m = -*l*,..,0,…*l*. In addition to these the polarization state of electromagnetic field in the resonator is also used to characterize the WGMs.

The optical coupling to the WGM resonators can be implemented in different ways [9]. The most common methods are *free wave coupling*, *Fluorescence coupling* and *evanescent wave coupling*.

In *free wave coupling* a far-field source is used to excite the WGMs. This form of coupling is very inefficient, because here only the rays having grazing incidence to the microsphere surface can excite a WGM mode.

Fluorescence coupling is a variance of free wave coupling. In this coupling scheme, the resonators doped with a fluorescent dye are excited with a far-field source. Since the fluorescence emission is isotropic, a significant fraction of emitted light can satisfy the condition for exciting different modes of the resonator. Here the coupling efficiency is better than the free wave coupling however this mode of excitation does not offer any mode selectivity.

The most efficient way of coupling to micro-resonators is *Evanescent wave coupling and it is* done by bringing the optical resonator in proximity with a coupler having an evanescent field, so that the proximity required for critical coupling is reached. This helps in tunneling of evanescent waves from the coupler to the resonator and vice versa. Evanescent wave coupling can be achieved using either a) Prism at the bottom, b) angle polished fiber, or c) tapered fiber as shown in figure 4.

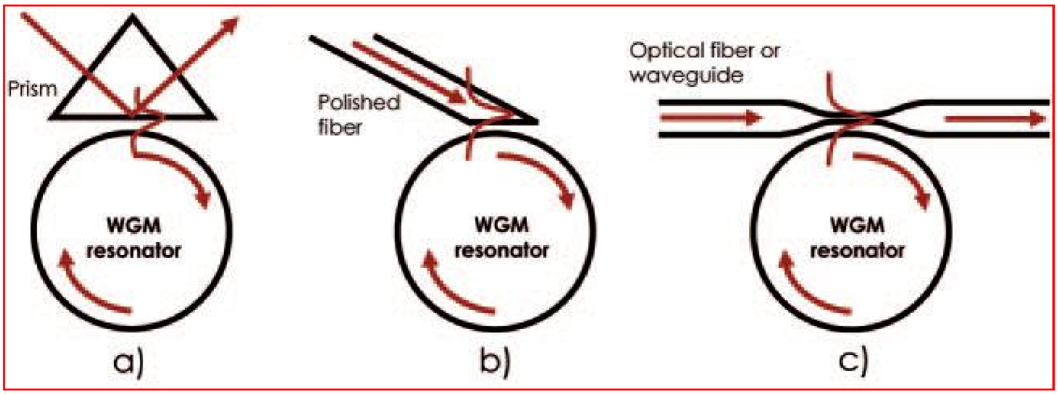


Figure 3: Evanescent filed coupling schemes [1]

Though evanescent field coupling is the most efficient way of coupling, the precise control of the distance between the microsphere and the evanescent field is difficult. The near-field probe structures also play an important role on the coupling. It would therefore be desirable if one can enhance the coupling efficiency of far-field excitation.

As a part of this project we are carrying out studies on the effect of the presence of gold nano-particles on the WGM of microspheres. The excitation of the attached gold nano-particles creates a localized SPR on the microsphere's surface and can act as the near-field source for exciting the microsphere WGMs [9]. The mutual interaction of WGM and plasmon field leads to splitting of modes and modification of plasmonic resonance.

For carrying out these studies I got myself familiarized with the MATLAB codes for Mie scattering [10] and used it for calculating scattering efficiency, extinction efficiency, backscattering efficiency, dependence of refractive index etc. In figure 4, we show the scattering efficiency for a polystyrene microsphere (diameter 25μm) in the wavelength range of 0.560 μm – 0.590 μm calculated using Mie Theory. The sharp spikes in the graph correspond to the whispering gallery modes. Using this program the dependence of refractive index of the microsphere and that of the medium on the WGM resonant wavelength (figure 5: a & b) was also studied. For calculating this, a polystyrene micro-sphere (RI=1.59) in water with a diameter of 25µm was considered. The results indicated that the shift depends on the relative refractive index *m* ($=n_{sphere}/n_{medium}$) and shows a red shift in the wavelength as *m* increases.

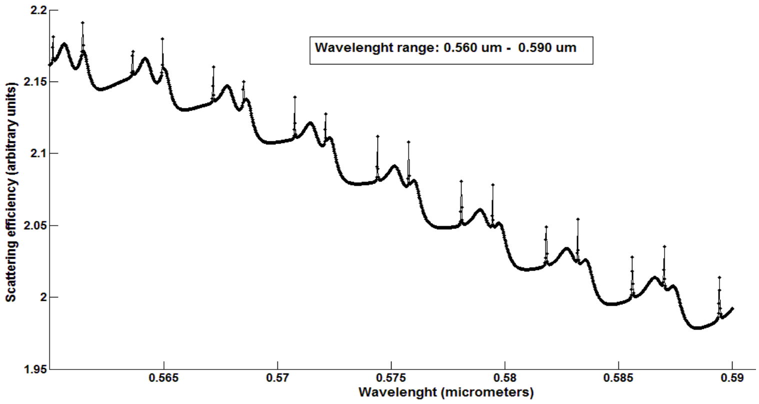


Figure 4: Scattering efficiency Vs Wavelength

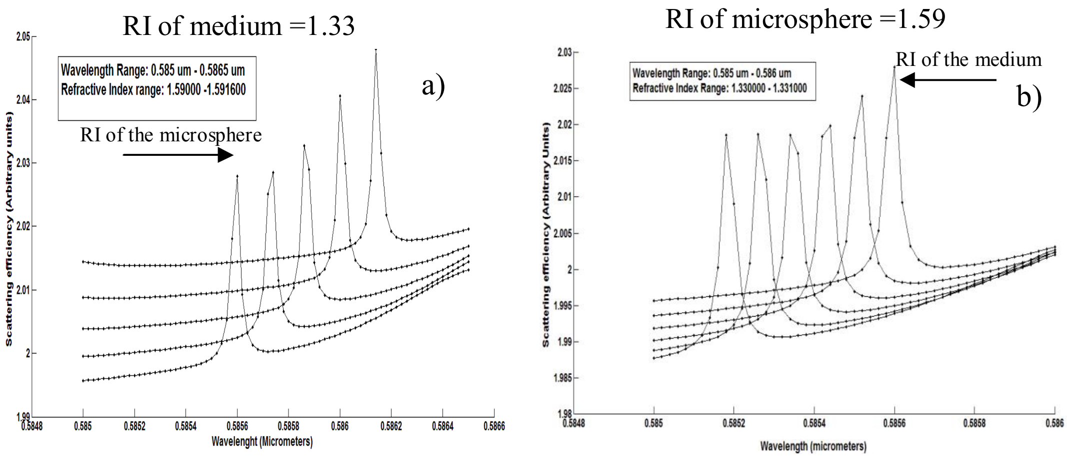


Figure 5: Plot of scattering efficiency by changing refractive index of a) microsphere, b) Surroundings

I have also got myself familiarized with the lab and the operation of Near-field Scanning Optical Microscope (NSOM) [11]. The NSOM system (figure 6) consists of: a) an illumination unit, b) collection unit, and c) a detection module. The illumination unit consists of a laser, polarization controller, feedback setup, objective and NSOM tip. The laser beam passing through the polarizer is made to focus on the NSOM tip having a small aperture through which the evanescent fields excite the microsphere. The collection unit consists of an objective which collects the forward scattered light from the microsphere and transfers it to the detection module. The detection module consists of a CCD and a PMT. The experimental data presented in this report were measured using the Alpha 300R Near Field Scanning Optical Microscope from WiTec GmbH, Germany. The near – field probe in this system is a cantilever with hollow-pyramid probes having aperture diameter of ~ 100 nm. The laser with the system is 442 nm He-Cd laser. For exciting WGM we use 50X objective. A 60X, 0.8NA objective was used to collect the scattered light from below the sample. The collected light was focused onto a 100µm diameter core multimode fiber which also acts like a pinhole for rejecting the stray light before it is delivered to a photon counting photomultiplier.

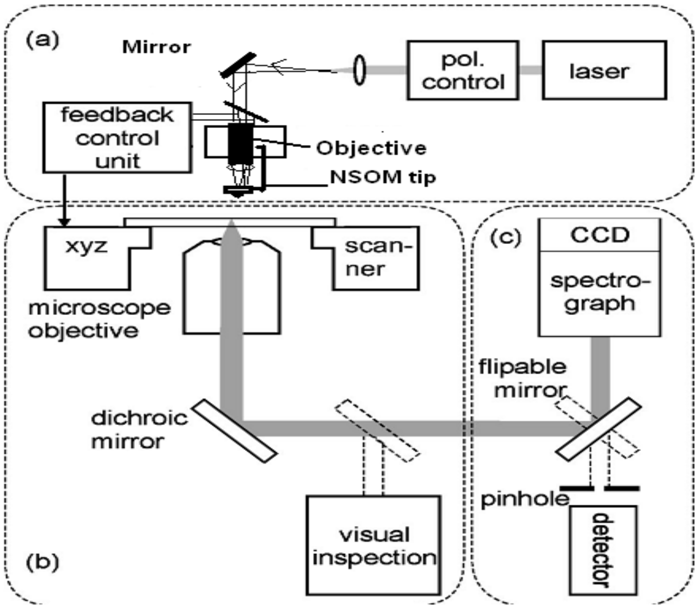


Figure 6: Schematic of NSOM system

We have carried out experiments for performing a spatial map of the near field scattering efficiency (henceforth referred to as excitation map) of the polystyrene microspheres of ~ 10 µm diameter. The Mie calculations for 10 µm polystyrene microsphere (n =1.59) shows that microspheres support resonance modes with sharp peaks in wavelength range of 440 nm-445 nm which overlaps with the laser wavelength (λ = 442nm) used in our experiment (see figure 7).

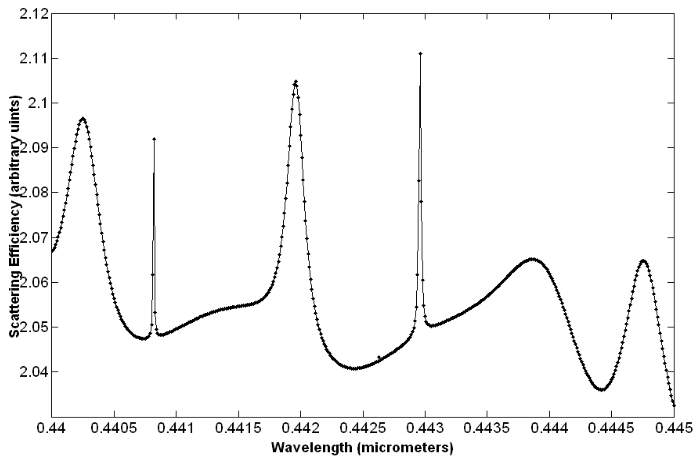
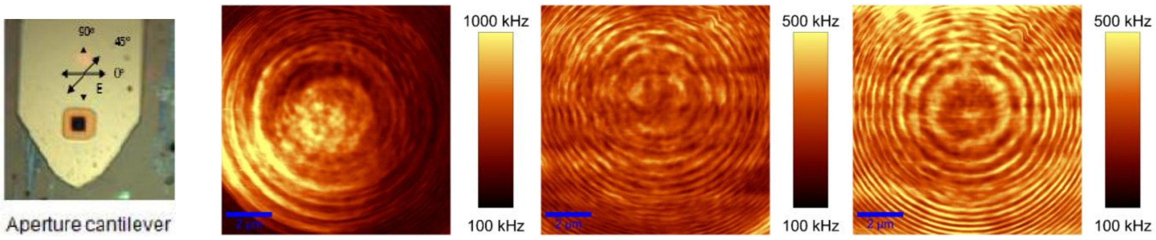


Figure 7: The scattering efficiency plot for 10µm polystyrene microsphere excited in the wavelength range of 440 nm – 445 nm.

The excitation map was recorded by scanning the NSOM probe (with 442nm excitation) in the contact mode with a step size of 20nm. The probe to microsphere distance was kept constant at ~10nm while performing the scanning over the top hemisphere of microsphere. This probe to sphere separation was chosen to ensure good signal to noise ratio and to avoid any damage to the probe.

The forward scattered light from the microsphere was collected by using the setup mentioned above. Measurements were carried out with three different orientation of the input linear polarization at the near field probe. Polarization axis was defined with respect to the cantilever axis (figure 8a). The excitation map as a function of input polarization state is shown in the figure 8 (b, c and d). A significant variation in the scattering intensity and pattern was observed with change in the input polarization state. Since the effective coupling between the near field at tip apex and microsphere occurs only when the wave vectors of two fields are matched, these observations suggests that the wave vector of near field at the probe varies with the input polarization. It may therefore be interesting to explore the use the polarization dependent tuning of the wave vector for improving the coupling between the evanescent field at tip apex and microspheres.



(a) (b) (c) (d)

Figure 8: Near field scattering efficiency map for 10μm polystyrene microsphere for three different incident polarization states b) 0^o c) 45^o and d) 90^o.

Presently we have used a laser with fixed wavelength (442 nm) for excitation of WGMs. Therefore, in view of the variation in the size of the microspheres and the concomitant shift of resonance modes excitation of WGMs was possible in only a fraction of microspheres for which laser wave length coincided with a WGM We now plan to use a super luminescent diode (SLD) source with peak wavelength of 840 nm and band-width of ±40 nm to study the excitation efficiency of the WGMs in microspheres. The Mie theory calculations for scattering efficiency in this wavelength range for 10 μm polystyrene microsphere is shown in the figure 9. It can be seen from the figure

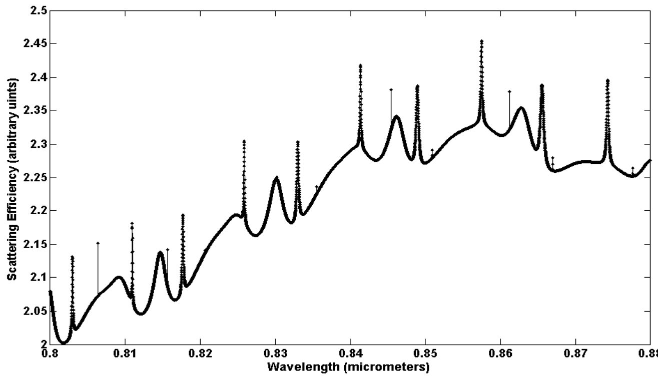


Figure 9: Scattering efficiency of 10μm polystyrene microsphere over the wavelength range of 800-880nm.

that several modes can be excited using the SLD source. In the next phase of this work we will study the nano-particle assisted coupling to WGMs using both far field and near field excitation in microspheres coated with gold nano-particles of different size and shapes.

References:

1. G. C. Righini, Y. Dumeige, P. F'eron, M. Ferrari, G. Nunzi Conti, D. Ristic and S. Soria, *"Whispering gallery mode micro-resonators: Fundamentals and applications",* Rivista del nuovo cimento 34, 7 (2011).
2. J. Ward, O. Benson, *"WGM microresonators: sensing, lasing and fundamental optics with microspheres",* Laser Photonics Rev.5, 553–570 (2011).
3. S. Soria , S. Berneschi, M. Brenci, F. Cosi, G N. Conti, S. Pelli & G C. Righini,*"Optical Microspherical Resonators for Biomedical Sensing",* Sensors 11, 785-805 (2011).
4. F. Vollmer & S. Arnold, *"WGM biosensing -Label free detection down to single molecules",* Nature Methods 5, xx –xx, (2008).
5. A. B. Matsko, A. A. Savchenkov, D. Strekalov, V. S. Ilchenko and L. Maleki, "Review of Applications of Whispering-Gallery Mode Resonators in Photonics and Nonlinear Optics", IPN Progress Report, 42-162, (2005).
6. M. Gomilšek, "*Whispering Gallery Modes*", 2011 (*mafija.fmf.uni-lj.si/seminar/files/**2011**_2012/wgm.pdf*).
7. O. Benson, S. G¨otzinger, A. Mazzei1, G. Zumofen, V. Sandoghdar, and L. de S. Menezes, "*Nanophotonics with microsphere resonators*", 2009 (*www.nano-optics.ethz.ch/publications/benson.pdf*).
8. C. F. Bohren & D. R. Huffman "Absorption *and Scattering by Small Particles"* (Wiley-New York, 1998).
9. S.I. Shopova, C.W. Blackledge, A.T. Rosenberger, "*Enhanced evanescent coupling to whispering-gallery modes due to gold nanorods grown on the microresonator surface*", Appl Phys B 93, 183-187, (2008).
10. Christian Matzler, "*MATLAB functions for Mie scattering and absorption",* (2002) (*www.iap.unibe.ch/publications/download/201/en/*).
11. R. C. Dunn, "*Near-Field Scanning Optical Microscopy",* Chem. Rev. 99, 2891−2927 (1999).