

Whispering gallery modes excited by two – photon absorption induced by an evanescent field

Smitha Kuriakose, Dru Morrish, Xiaosong Gan, James W. M. Chon and Min Gu[†]

Centre for Micro-Photonics,
Faculty of Engineering and Industrial Sciences,
Swinburne University of Technology,
PO Box 218, Hawthorn, VIC. 3122, Australia.

ABSTRACT

In this paper, we report the excitation of whispering gallery modes (WGM) using a focused evanescent field. A focused evanescent field generated by total internal reflection at the cover glass – air interface was used to induce two-photon absorption in fluorescent polymer microcavities. By using a focused evanescent field it was possible to effectively couple light into the whispering gallery modes by the efficient overlap between the excitation volume and the cavity modes. The recorded whispering gallery mode spectra using an evanescent wave showed up to 38% enhancement in the spectral characteristics.

Keywords: whispering gallery modes (WGM), evanescent wave, microcavities, multiphoton absorption

1. INTRODUCTION

Optical resonators form integral part of most of the optical networks. When light enters a dielectric microsphere having a high refractive index than the surroundings, the light gets total internally reflected continuously, and at characteristic frequencies which are dependent on the ratio of size of the resonator to the emission wavelength, resonant modes are set up in the microsphere which are termed whispering gallery modes(WGM).

It was Lord Rayleigh who first observed sound waves or ‘whispers’ travelling around the curved surface of a dome at St.Paul’s cathedral in London¹. The theoretical understanding of Whispering Gallery Modes could be derived from the works of Debye² and also from Mie’s theory³. Optical whispering gallery modes were first demonstrated in millimetre sized CaF₂:Sm⁺⁺ crystalline resonators immersed in liquid hydrogen⁴. Since then different optical resonators in the shapes of cylinder, toroid, ring, disk, post and other modifications have been demonstrated. All of the earlier studies showed the enhancement of elastic absorption and scattering and optical levitation forces when the incident wavelength was near the natural eigen modes of oscillation of the dielectric sphere. In 1980, sharp WGM peaks were observed in the fluorescence spectra of single dye-doped polystyrene beads suspended in water, which was the first experimental demonstration of structure resonances resulting from the internal emission of inelastic radiation by fluorescing molecules embedded in a microsphere⁵.

2. FOCAL VOLUME ANALYSIS FOR COUPLING

[†] Author to whom correspondence should be addressed; electronic mail: mgu@swin.edu.au

Effective coupling of light to the microcavity is the most critical requirement for the feasibility of good optical resonators. Evanescent field generated by total internal reflection on the surface of a prism⁶ or by a guided wave^{7,8} has been popularly employed to efficiently transfer optical energy to resonators. The evanescent field generated by total internal reflection on the surface of a prism is characterised by strong confinement in the axial direction due to the exponential decay of the evanescent field but has a wide area illumination in the transverse dimension. An alternate and popular method of coupling to the microcavity is by using a focused beam⁹, where the three dimensional confinement is achieved by the focusing by a high numerical aperture objective. But the far field focal spot by a high numerical aperture objective is elongated with three times the size in the axial dimension as compared to the transverse. Such a confinement can be further enhanced by using two-photon absorption where the fluorescence emission is highly confined in the three dimensional space.

We have previously used the two-photon absorption process for excitation of whispering gallery modes, where the three dimensional confinement provided the freedom to efficiently tune the performance of the microcavity resonator¹⁰. It was demonstrated that the more it is possible to confine the excitation spot within the cavity, the better would be the feasibility to finely localise the excitation spot within the cavity which in turn helps to selectively tune the cavity characteristics by spatial localisation of the probe. This provided the motivation to further confine the coupling illumination by using a focused evanescent field¹¹. In this paper, we use the evanescent field generated by total internal reflection of a highly focused beam incident at the cover glass interface to couple optical energy into the microcavity. Such an evanescent field with k vectors in all 360 degrees would contribute to a much stronger excitation of optical modes within the microsphere.

The schematic representation of the geometry for focal evanescent coupling to a cavity is as shown in figure1.

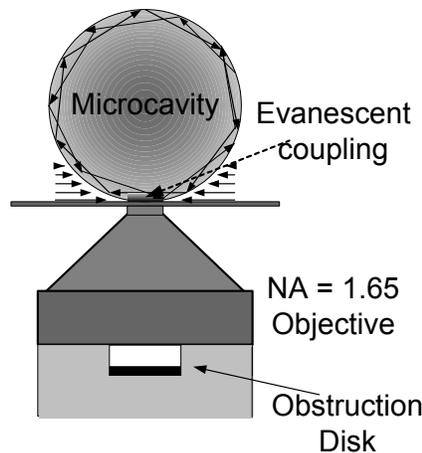


Figure 1. Schematic representation of focused evanescent coupling to the cavity

A suitable obstruction disk of size ϵ , normalized with respect to the entrance aperture of the objective is used to centrally block the propagating rays and thus generating an evanescent field by total internal reflection at the coverglass - air interface, which was employed to couple light to the cavity. In order to quantify the efficiency of focal confinement in coupling to a microcavity, it would be desirable to compute the confinement required for a microcavity of a given size. The thickness of the shell confining the total internally reflected rays within a microsphere resonator of diameter $10 \mu\text{m}$ was

computed to be about 0.8 times a micrometer and by confining the excitation spot well below this thickness would lead to the efficient overlap of the excitation volume and the cavity modes. The obstruction disk size of $\varepsilon = 0.6$ corresponded to the critical size for total internal reflection for oil-air interface and a value of $\varepsilon = 0.96$ corresponded to the critical size for total internal reflection for oil-polymer interface.

3. EXCITATION OF WHISPERING GALLERY MODES - EXPERIMENT

A Titanium - Sapphire laser (SpectraPhysics Tsunami) at a wavelength of 800 nm and at a repetition rate of 80 MHz was used to excite the optical microcavity. The schematic diagram of the experimental setup is shown in figure 2. Fluorescent yellow-green microspheres with an absorption peak at 486 nm were used in order to ensure efficient two-photon absorption. After expanding and collimating the beam, an obstruction disk of suitable size was inserted so as to block the central propagating component and to generate the evanescent field. The annular beam was focused by NA = 1.65 (Olympus, 100X) objective and the focused beam underwent total internal reflection at the coverglass – air interface generating an evanescent field which was coupled to the fluorescent microcavity attached to the coverglass. The resulting spectra were analysed using a spectrograph (Acton Research Corporation) with a resolution of 0.1nm and also the excitation was imaged using a CCD camera.

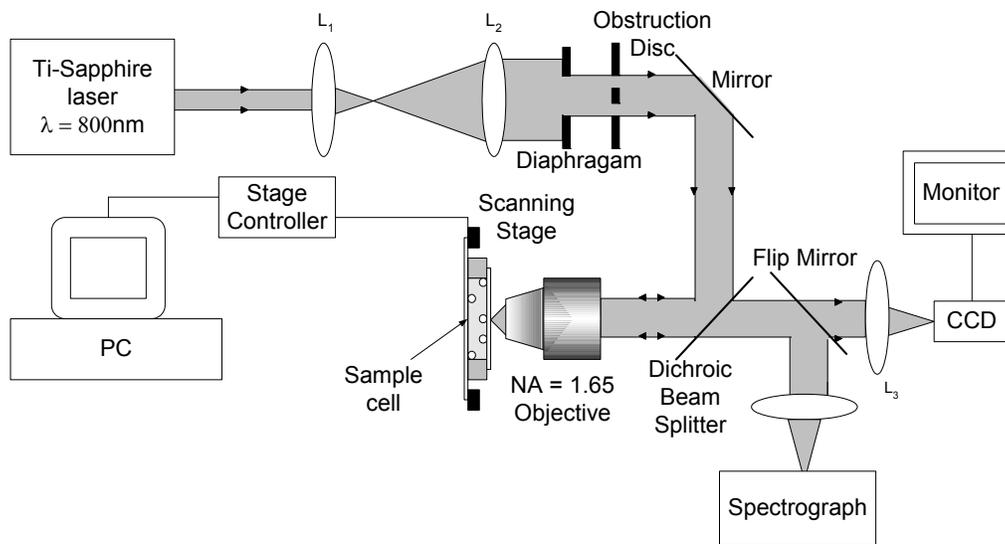


Figure 2. Schematic diagram for the experimental set up for exciting whispering gallery modes

In order to demonstrate the quadratic nature of the multiphoton absorption, the fluorescent intensity from the whispering gallery spectra excited within a 5 μm diameter microsphere (Duke Scientific) was recorded as a function of the input power for both far field ($\varepsilon = 0$) and near field ($\varepsilon = 0.64$) excitations.

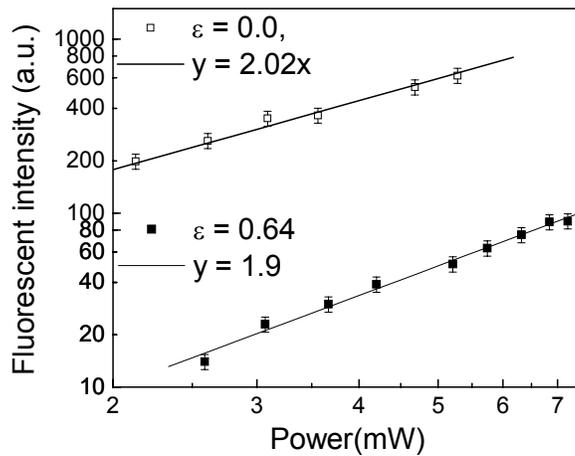


Figure 3. Log-log plot of the fluorescent intensity as a function of the input power

The log-log plot of the output versus input power is shown in figure 4 which when fitted to a straight line gave a slope of 2 demonstrating the two-photon absorption induced by both far field and evanescent excitations.

Whispering gallery modes were excited within the 5 μm fluorescent microspheres using both far field and near field beams. Figure 4a shows the resonant spectrum recorded when whispering gallery modes were excited using an unobstructed beam focused by NA = .165 objective. Figure 4b shows the resonant spectrum recorded using a focused evanescent wave with an obstruction disk size of $\epsilon = 0.77$.

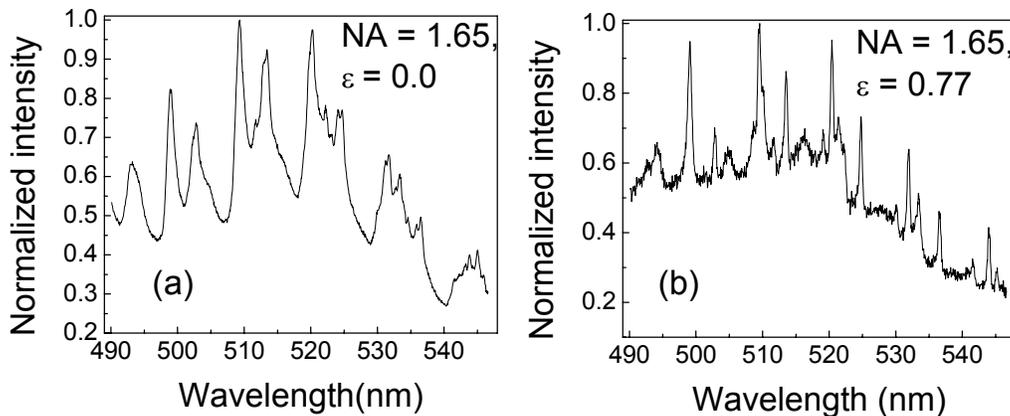


Figure 4. Fluorescent spectra recorded from whispering gallery modes excited by (a) far field illumination (NA = 1.65, $\epsilon = 0$), and (b) focused evanescent illumination (NA = 1.65, $\epsilon = 0.77$).

It was found that the full width at half maximum (FWHM) of the recorded spectrum decreased by 38.72% which showed a dramatic improvement in the photon storage time within the cavity when the illumination was changed from a propagating far field to a localized focused evanescent wave. This suggests that the coupling to optical microcavities could be enhanced by using a localised light field which is in this case a focused evanescent wave.

By using such a focused evanescent wave, it is also possible to excite non-linear phenomenon such as multiphoton absorption and the technique could also be used to as sensors for biomolecules by properly analyzing the surface analytes using changes in characteristic properties such as refractive index change, fluorescence etc.

ACKNOWLEDGEMENT

The authors thank the Australian Research Council for its support.

REFERENCES

1. J. W. Strutt (Lord Rayleigh), *The Theory of Sound*, New York: Dover (1945).
2. P. Debye, "Der Lichtdruck auf Kugeln von Beliebigen Material," *Ann. Phys.*, **30**, 57 (1909).
3. G. Mie, "Beitrage zur Optik Truber Medien," *Ann. Phys.*, **25**, 377 (1908).
4. C. G. B. Garrett, W. Kaiser, and W. L. Bond, "Stimulated Emission into Optical Whispering Gallery Modes of Spheres," *Phys. Rev.* **124**, 1807 (1961).
5. R.E.Benner, P.W.Barber, J.F.Owen and R.K.Change, "Observation of structure resonances in the fluorescence spectra from microspheres", *Phys.Rev.Lett.*, **44**, 7 (1980).
6. M. L. Gorodetsky and V. S. Ilchenko, "Optical microsphere resonators: optimal coupling to high- Q whispering-gallery modes", *J. Opt. Soc. Am. B* **16**, 147 (1999).
7. J. C. Knight, G. Cheung, F. Jacques and T. A. Birks, "Phase-matched excitation of whispering-gallery-mode resonances by a fiber taper", *Opt. Lett.* **22**, 1129 (1997).
8. M. Cai, O. Painter and K. J. Vahala, "Observation of Critical Coupling in a Fiber Taper to a Silica-Microsphere Whispering-Gallery Mode System", *Phys.Rev. Lett.* **85**, 74 (2000).
9. P.G. Schiro and A.S. Kwok, "Cavity-enhanced emission from a dye-coated microsphere", *Opt. Exp.* **12**, 13 (2004).
10. D. Morrish, X. Gan and M.Gu, "Observation of orthogonally polarized transverse electric and transverse magnetic oscillation modes in a microcavity excited by localized two-photon absorption", *Appl. Phys. Lett* **81**, 5132 (2002).
11. M. Gu, J.B.Haumonte, J.W.M. Chon and X. Gan, "Laser trapping and manipulation under focused evanescent wave illumination", *Appl. Phys. Lett* **84**, 4236 (2004)