INTRODUCTION

Whispering-gallery-mode (WGM) resonances are electromagnetic resonances that occur in circularly symmetric dielectric particles. They correspond to light trapped in circling orbits just within the surface of the particle, being continuously totally internally reflected from the surface. Under these circumstances the leakage of light from the particle can be extremely low.

The high-*Q* values and small mode volumes of these WGM resonances in these micro resonators make this system of interest for a number of fundamental and applied studies. The principle of WGM is originally taken from the acoustical waves propagating within the circular galleries of old architectures.

As the optical resonances in these structures are a function of their morphology (*i.e.* their geometry) and dielectric properties (refractive index), they are sometimes referred to as MDRs (Morphology-Dependent Resonances); although the name is not much used as WGM.

Whispering-gallery modes are a specific class of spherical modes that are used to study many optical problems. Renewed interest in WGMs has inspired creative investigations into many different micro technologies using different micro structures like micro spheres, micro cylinder, micro disk and micro toroid. Microspheres, in particular, are very appealing objects because of the small effective volumes of their WGMs and their high-*Q* factors. Such micro resonators are shown to have potential use in many areas, including cavity quantum electrodynamics, laser stabilization, micro lasers, nonlinear optics, and evanescent-wave sensing.

THEORY OF WGM

An optical resonance will occur when the optical path length travelling inside the resonator is an integer multiple of wavelength. Here the path length is the circumference of a circle. So WGM frequencies in an optical fibre, or indeed any cylindrical resonator, are reasonably well approximated by matching an integral number of wavelengths to the resonator circumference, i.e.,

$$m\left(\frac{\lambda}{n}\right) = \pi d \quad \text{or} \quad \nu = \frac{mc}{\pi d n}$$

where m is an integer, λ is the free space wavelength and v the frequency of the light used to excite the resonator, n is the refractive index of the resonator, and d is the resonator diameter. This treatment becomes more accurate as m increases and the path taken by the light within the resonator becomes more closely approximated by a circle. A key result is that both the WGM frequencies and the frequency spacing between adjacent modes are inversely proportional to the resonator diameter. However, in reality the true path is 'polygonal' in nature, such that the path length is shorter, and therefore the resonant frequency higher, than predicted by this simple model.

PROPERTIES OF WGM

WGM not only temporally confines light but also spatially confines it too.

The measure of an optical resonator or cavity's ability to confine light of a given frequency v_0 is usually expressed in terms of a 'quality factor' or 'Q-factor', Q.

$$Q = 2\pi v \frac{P_{stored}}{P_{lost}} = \frac{v_0}{\delta v}$$

where P_{stored} and P_{lost} are the power stored within the cavity and lost from the cavity, respectively, and δv is the spectral linewidth of the cavity mode at frequency v0. The ultimate Q of a perfect microsphere resonator is around 10^{10}. Experimentally measured Q factors are generally much lower than this due to scattering from surface roughness and impurities, absorption by the material, and simultaneous excitation of multiple closely spaced modes.

Spatial confinement is defined by the mode volume which can be defined as the energy density of the optical mode.

EXCITING WGM INTO MICRORESONATOR

There are three methods to couple the light into the microresonator and excite the WGM.

The first method is the free coupling of radiation into the microsphere. This method is inefficient because the radiation exchange is very small.

The second method is coupling through the frustrated total internal reflection by a prism. The coupling efficiency reported is 80%. Prism couplers typically are not ideal because of the large number of possible output modes.

The third method and most commonly applied is using optical fibers like side polished fiber, fiber tapers, etched fibers etc.

Tapered fibers are most efficient and efficiency is reported to be almost 100% till date. It is most beneficial as most of the fundamental mode leaks as the cladding mode in the tapered region and then couples back as the core fundamental mode into the untaper region. Required operational principles of the coupling devices are

based on 1) phase synchronism, 2) optimal overlap of the selected WGM and the coupler mode,3) selectivity, and 4) criticality.

Ideally, the resonator should be critically coupled to the fibers. The condition of critical coupling is a fundamental property of waveguides coupled to resonators. It refers to the condition in which internal resonator loss and waveguide coupling loss are equal for a matched resonator–waveguide system, at which point the resulting transmission at the output of the waveguide goes to zero on resonance. It is easy to satisfy these conditions using fiber taper.

<u>REQUIREMENTS FOR ACHEIVING WGM</u>

As mentioned above, critical coupling occurs only when the fiber transmitted is completely annihilated. It occurs only when the light intensity which is not coupled into the fiber exactly matches the intensity of the coupled light back from the microsphere at 180^0 leading to destructive interference.

Thus, if a broadband source is used, then there will be Lorentzian dips corresponding to the resonant wavelengths as shown in figure.

The main components needed:

1). Broadband Source

2). Microsphere

3). Optical fiber thinned in between to provide the evanescent field

4). Optical Spectrum Analyzer (OSA) as detector

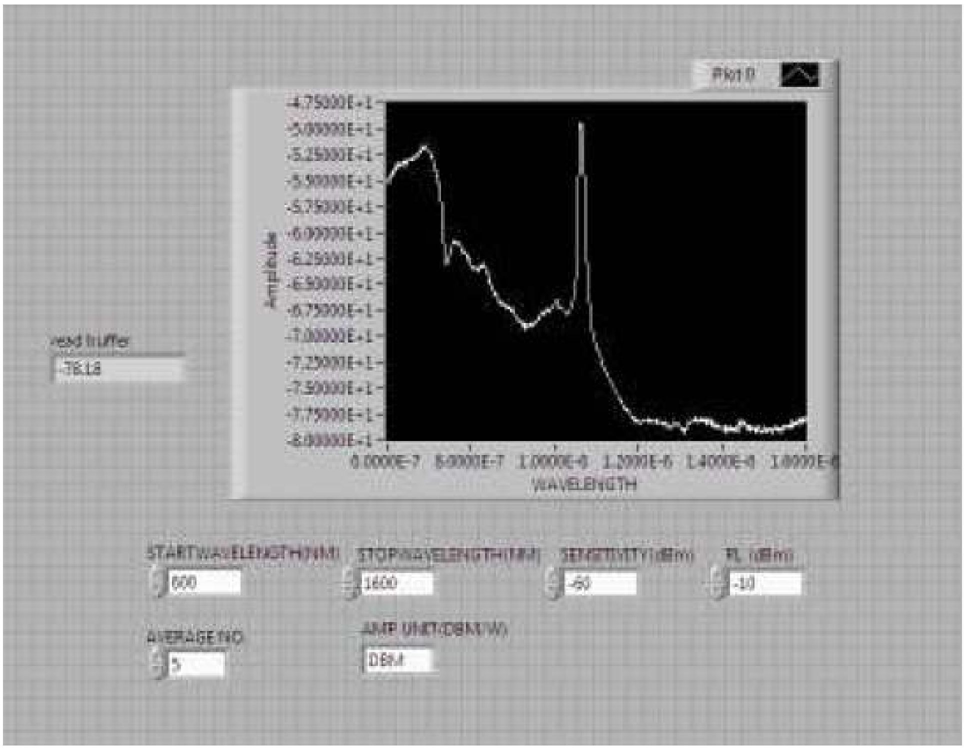
The digitally recorded transmission spectrum will help to identify the resonant wavelengths as Lorentzian shaped dips in the transmission spectrum.

The main steps taken for achieving the WGM are:

AUTOMATION OF OSA

Optical Spectrum Analyzer(OSA) is used to obtain the power of the source versus frequency. There is a need for real time monitoring of the spectrum of the broadband source. So, the OSA had to be automated to obtain the spectrum to the computer and save and analyze the data in it.

Labview is a software to interface the optical or electronic instruments to computer. It needs a GPIB cables to connect the electronic equipment to the computer. We can access the equipment by writing corresponding labview program.

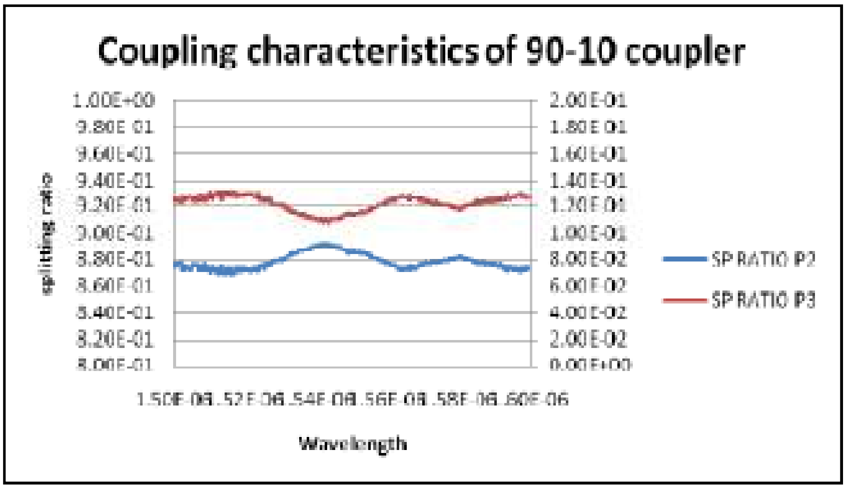


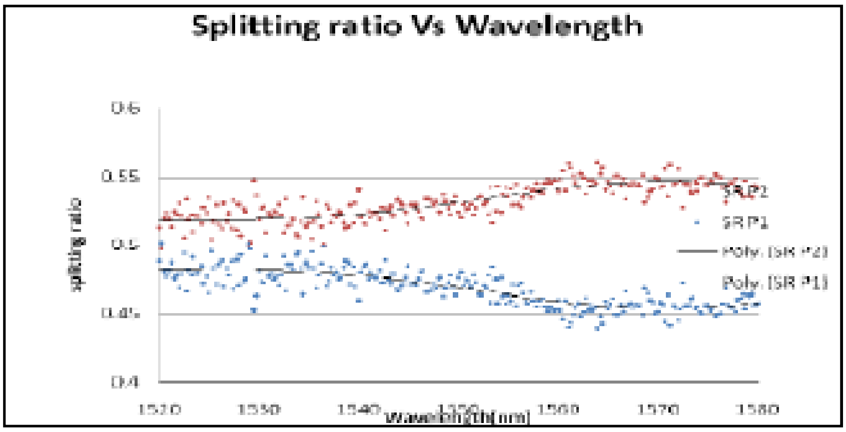
RESULTS:

Using the above LABVIEW program, the coupling characteristics of two couplers were checked as shown in the below fig. The input port of the coupler is connected to the broadband source and the one of the output port is connected to the OSA. The LABVIEW pro the computer and the data for the first output port are saved in the EXCEL file. Then, another output port is connected to the OSA and again the same procedure is repeated. Thus, the output powers are obtained with their initial input powers.

$$Splitting\ Ratio\ =\ \frac{Power\ of\ one\ output\ port}{Sum\ of\ both\ the\ output\ ports}$$

A graph is plotted for the splitting ratio as calculated by the above formula.In the case of 50-50 coupler, the splitting ratio in 1310 and 1550nm was obtained as 50.3 and 52.9% which matches with 50.6 and 52.9% for 1310 and 1550nm respectively, specified by the manufacturer.





<u>ETCHING OF THE FIBER:</u>

As the evanescent wave coupling from the fiber is used to excite the WGM in the microsphere and the evanescent field exponentially decays and becomes zero at the cladding air boundary, the cladding has to be reduced or removed so that the interaction of the evanescent field with the surroundings is enhanced.

It is found in many literatures that the core diameter should be atleast in sub nanometer range for the effective excitation of the WGM. Also, efficiency of coupling through tapered fiber is high. Since, we need a high power laser for heating and pulling the fiber for tapering it; which is not available in the lab, we used etching of the fiber as an alternative.

a). Experimental setup:

A small portion of the fiber jacket is stripped and cleaned with isopropyl alcohol. It is placed on a small plastic cover over a glass slide. The two ends are held tight on the slide using UV curated epoxy. Then, the slide is placed on a heater with a constant temperature. The two ends of the fiber are connected to a laser source and a detector respectively. A few drops of HF is put on the stripped portion of the fiber and the power is real time monitored using Labview program. When the power starts decreasing rapidly, drops of distilled water is used to clean the HF off the fiber.

We have prepared fiber with core diameter upto 2 microns with this method but the uniformity of the etched portion is major problem which leads to larger scattering of the light and drastically decreases the coupling efficiency.

So, we tried another method to develop a tapered fiber using flow etching. In this case, a fiber is made to touch a drop of HF and during the etching, the HF flowed from the droplet and traversed along the fiber. This surface tension driven flow is called Marangoni effect and it provides two benefits: firstly, because of the flow of HF along the fiber, its concentration is decreased, thereby, a graded profile etching occurs leading to a tapered profile. Secondly, the surface corrugations due to aggregation of HF are also reduced due to the flow.

b).Experimental setup:

We first stripped the plastic jacket of fiber (Sterlite Company (SMF-28)) and cleaned it with isopropyl alcohol. The fiber is clamped onto two XYZ translation stages and the two ends are connected to the laser source and detector (HP 8153A Lightwave multimeter, wavelength 1550nm) respectively. A droplet of concentrated HF acid (40% by weight) is placed onto plastic sheet. The stripped part is kept a little higher on the glass slide so that it can only touch the droplet. When the etching starts, the optical power reading in the detector starts to lower. The experiment is carried out in room temperature. The controlling of the process is difficult once the cladding is removed. So, we started to wash off the HF once the optical power had significant dip. The fiber is cleaned using distilled water. The HF is diluted by adding a few drops of distilled water. And again, the process is repeated using this HF.

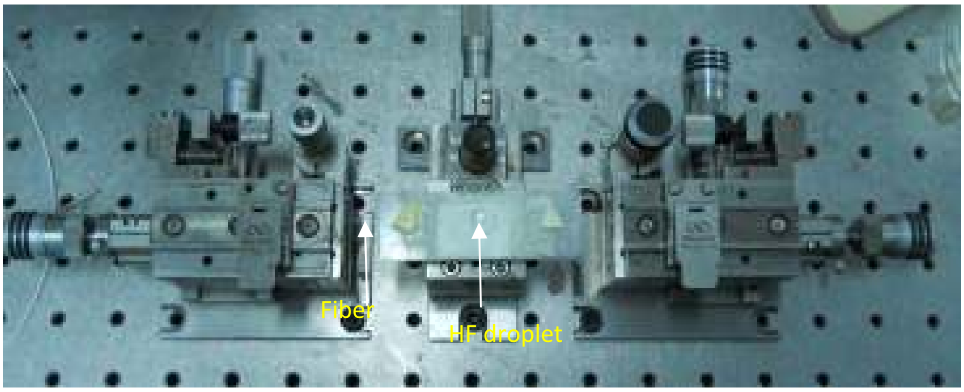


Fig: Experimental setup of etching process

The taper length depends on the size of the droplet.

We were able to achieve around 2 microns with lesser surface roughness. With this fiber, even a little coupling to microsphere was seen.

FABRICATION OF MICROSPHERES

We are using fiber splicer machine to fabricate it. The electrode mode of the splicer is chosen. The tip of the fiber is arc melted and it takes spherical shape due to surface tension. The contact area between the spherical and the stem part should be less for the elimination of coupled light through the stem. The contact area is determined by the extent of the etching of the fiber.

EXPERIMENTAL SETUP FOR ACHIEVING WGM

We are using an automated translation stages-two XYZ stages and two CCD cameras focusing horizontally and vertically. The fiber is clamped to one stage using fiber holder and microsphere is clamped through the stem part to another stage using fiber holder. The fiber is kept stable with the ends connected to SLED source and OSA and microsphere is traversed along the fiber using the stage. The position of the microsphere on the fiber is viewed in the two TV monitors.

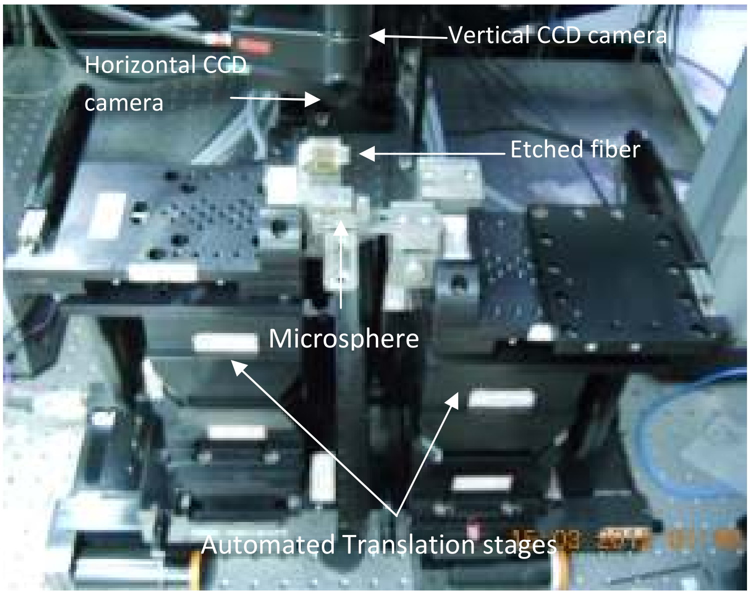


Fig: Experimental Setup

Results:

The decrease in power level was seen in the OSA when the microsphere was placed on the fiber at a point confirming that the coupling of light is occurring but no periodic dips are seen which can be due to problems in coupling light back to the fiber.

CONCLUSION:

We were able to etch fibers upto 2 microns and also with a tapered profile. Also, microspheres were fabricated. We were able to see the power loss which confirmed coupling of light into the microsphere. But it can be observed that the evanescent field out of the core is not enough for a considerable change in power.