THE SCIENTIFIC AND TECHNOLOGICAL RESEARCH COUNCIL OF TURKEY (TÜBİTAK)

SCIENCE FELLOWSHIPS AND GRANT PROGRAMMES DEPARTMENT

Final Report

Project Covered (01/07/2014- 30/06/2016)

Project Number: 114C030

Project Title: "Cavity Enhanced Spectroscopy with Droplet Resonators"

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Summary of Project Progress *(Please report progress of the project over the last term (not more than 1000 words)*

The main goal of this project was to work with the resonators occurring in nature, such as liquid droplets that use the same mechanism as dielectric resonators to trap light and do a comparative study between nature and a variety of technologically relevant resonator designs that are based on the same confinement principle. Whispering gallery modes (WGMs) -based sensing in droplets was relatively unexplored. So, with this motivation, it was proposed to investigate the use of WGMs for monitoring processes inside these droplets mainly for its application in sensing. Particularly the properties of WGMs of liquid droplets of different volume and chemical content held in different refractive index for its application in chemical and bio-sensors.

To achieve the objective of the proposal the Droplet Resonators were produced by using various techniques and then cavity enhanced spectroscopy was performed. This detection scheme uses a cavity to enhance the effect of small losses. Here, the absorption is calculated from the mirror-transmitted intensity of WGMs. The absorber of interest is placed in a high-finesse optical cavity bounded by two high reflective surfaces (droplets in our case). The transmission signal strength is measured (in terms of Quality Factor, Q of WGMs) with and without absorber and from the difference the absorption coefficient or concentration can be deduced. So, to perform cavity enhance spectroscopy, we used a droplet as cavity and observed the WGMs in scattering signal.

WP1 was focused on the design and optimization of the Cavity Ring down spectroscopy setup together with the PDH locking system.

WP2 was focused on the design and optimization of the optical tweezers and dual beam fiber trapping techniques to trap surface supported emulsion droplets and study their comparative spectroscopic behavior. Both the tweezers are capable to trap particle very robustly, the difference is in their approach to facilitate different studies. Also, a dual beam trap has the ability to change the shape of the droplet.

WP3, was focused mainly on the generation of uniform droplet of various sizes and design of droplet resonators.

In **WP4**, it was proposed that the single beam optical tweezers setup during the second WP will be used to trap nonvolatile liquid droplets in the air or in liquid.

The **WP5** (final) was mainly focused on investigating the ability of these trapped droplets to act as droplet resonator and facilitate various spectroscopic measurements on optically trapped droplets. Various applications involving sensors arising from the proposed work were also proposed to be investigated in final WP.

The sensitive dependence of whispering gallery modes (WGMs) to changes in refractive index, morphology, composition and temperature as well as the ability of the evanescent field to probe beyond the micro droplet surface, allows for the development of compact photonic sensors based on liquid droplets. These devices would offer low cost, compact means for detecting biological and chemical species, stress/pressure, and temperature changes. These features enable fast generation and characterization of micro and nano- scale volumes with high sensitivity, hence make it attractive for various sensor applications.

During the last two years of the project, first the experimental setup to perform the study on droplet resonator was designed during WP1 and WP2 of the project. Then, under WP3, the droplet resonator (DR) which in our case was an immersion oil (benzyle benzoate) was prepared using a typical flow focusing microfluidic chip method. The selection of appropriate chemicals was done on the basis of their refractive indices suitable to perform total internal reflection inside the droplet.

A single beam optical tweezers were designed to trap and hold oil droplet at a fixed place, so that spectroscopic measurements can be performed easily. Under WP4, the setup dedicated to work with droplet resonator was designed and optimized. Arrangements were also made to excite the droplet using a Telecom laser (1550nm) and record scattering signals scattered from the droplet (WP5). The droplet was expected to emit WGMs when excited by a sweeping laser, thus behaving as a droplet resonator. This **goal was successfully achieved** and I was able to observe WGMs by recording the scattered light from the droplet. The droplet resonator designed were used to explore the sensing

capability. Four different chemicals were used to test the droplet resonator as a sensor. However, we had little doubt about the modes observed using multi-mode fiber as they could also be coming from the fiber. Although we observed the FSR corresponding to the diameter of the droplet but the presence of other modes apart from FSR were difficult to explain. So, to verify our results, we decided to repeat the whole experiment with single mode fiber. It was a good decision to repeat the experiment with single mode fiber as then we got some very interesting results that lead to a publication in a reputed journal (JOSA B).

Another experiment on WGMs based humidity and temperature sensing was also done on the microdisc resonator. We studied, humidity sensing abilities of SU-8 based optical microdisc resonators. A tunable telecom laser (1500-1620 nm) was coupled from an optical fiber to SU-8 waveguide using an end - face coupling. When the wavelength of the light is in resonance with the SU-8 microdisc, the light couples to the whispering gallery modes (WGMs) of the microdisc. Therefore, transmission dips are observed while the wavelength of the light is swept in a certain wavelength range. This result is sent for publication in the journal Sensors and Actuators B.

In yet another attempt, we are trying to achieve WGMs coupling in a cylindrical cavity using a tapered fiber. This experiment is in progress and is expected to send for publication soon.

Every result and every new trick that is learned in the progress in addition to the profound experience of the host scientist, helped to find an appropriate method to establish WGMs for monitoring processes inside these droplets. The aim of this project was to deliver a sustainable concept of cavity based WGMs through experimental observations, which we achieved successfully.

I presented the current research outcomes in three international (PIERS, WPC 2015, EMN droplet meeting) and three national conferences. I successfully published my observations in a peer reviewed journal (JOSA B). I presented this work in the PIERS conference 2015 in Prague. Also, I had a chance to present my research in an invited presentation at the EMN droplet meeting from 9-13 May in Spain.

The detailed results are explained in progress report below.

1. Work Progress and Achievement in the last two years

As mentioned in the summary of the proposal, five work packages (WPs) were proposed to achieve the proposed goal of the project. The project was implemented mainly in two parts. The goal of the first part was to prepare Droplet Resonators (DRs) using flow focusing techniques and then perform some basic spectroscopic analysis to observe and record the WGM signals. This was necessary to see the performance of the designed Droplet resonator. The second part was to study the cavity enhanced spectroscopy from the cavity in transmission or scattering by PDH locking with CRDS experiments.

During the whole tenure of the project (i.e. Last two years), I dealt with all the five WPs of the project goal and successfully observed that the droplet resonator designed was successful in scattering WGM modes. Following are the achievements during the tenure of the project:

1. **Microfluidic chip fabrication by soft lithography. Two chips were designed, one for generating the droplets and the other was used in the experimental setup to access the droplets in a liquid medium.**
2. **The droplets of sizes varying from 10 to 40 µm were generated in the microfluidic channel and then transported to other microchannel for the experiment.**
3. **The ability of natural droplets to act as real resonators was successfully analyzed and were studied to be used as sensors in the future.**
4. **Single beam tweezers to trap and to achieve efficient coupling to the droplets inside microchannel was designed and optimized. Trapping laser has wavelength of 1070nm.**
5. **A Multimode and singlemode fiber was used to excite the droplet with laser (SANTEC) having wavelength range 1550-1620 nm and the scattering signal was recorded by a detector placed perpendicular to the sweeping laser.**
6. **Four different concentrations of seed and olive oil were used to test the ability of the resonator to act as sensor based on their Q-factors. This work got published in Piers conference, 2015.**
7. **A single mode fiber was used to excite benzyle benzoate droplet and coupling to WGMs was controlled by Optical tweezers by trapping the droplet inside a microfluidic channel, this work got published in JOSA B journal, 2016.**
8. **Humidity sensing abilities of SU-8 based optical microdisc resonators were also investigated. The work has been sent for publication in the journal Sensors and Actuators B.**
9. **Cavity ring down spectroscopy (CDRS) experiment with PDH Locking system were optimized and experiment is going on.**

I purchased few optical components and consumables that were needed for performing the experiments. We successfully achieved cavity enhanced measurements through scattering. We couldn't complete the CDRS with PDH locking cavity experiments yet but in due course of time it will be done.

2. Progress Report *(Please provide a report on the progress made on the project grant over the last term. Please report on the achievement of significant milestones in the project and if milestones have been missed, please explain the reasons why. The report should not exceed 10 pages excluding references.*

Light in a microspherical cavity is confined by total internal reflections (TIRs) at the interface between microsphere and the surrounding medium. The electromagnetic waves coupled into the cavity or emitted from a gain medium inside the cavity, that meet the requirements for constructive interference form cavity resonances are called whispering gallery modes (WGMs) [1, 5]. The energy stored in the cavity at resonance frequency increases, due to large quality factors (Q-factors) of these resonances. Droplet resonators, the microfluidic equivalent of solid spherical resonators are among the oldest WGM resonators, first studied more than 30 years ago [1] and shown to exhibit ultra high Q-factors.

These low-loss resonant modes allow droplet lasers to operate at low threshold pump powers. Liquid droplets are easy to produce using aerosol generators in air or flow focusing / T-junction geometries in a microfluidic chip. Upon generation, droplets can be captured and manipulated using optical micromanipulation techniques such as optical tweezing. In addition, water-based droplet cavities are also biologically compatible, permitting the use of aqueous solutions of biologically relevant molecules as laser gain media.

The self-organized and molecularly smooth surface of liquid droplets makes them attractive as optical cavities with very high quality factors (Q). The proposal aimed to explore the droplet optical cavities for various applications. The optical properties including scattering excitation was explored, and the sensitivity of microdroplet resonators was studied in details. Optofluidic implementations of microdroplet resonators were explored with emphasis on the basic optomechanical properties. The properties of whispering gallery modes (WGMs) of liquid droplets of different volume and chemical content held in different environment (of different refractive index) were investigated for its application in chemical sensors. The proposal also aimed to attempt the first rigorous study of PDH locking and cavity ring-down spectroscopy (CRDS) of a liquid droplet. We will also benefit from high sensitivity of CRDS to achieve bio-sensing with droplet resonators.

The sensitivity of sharp WGM resonances to small changes in, and around the environment of microcavity, such as temperature, refractive index or foreign contamination, make them one of the most sensitive probes for chemical or biological sensing applications. Chemical and biological detection with Q-factor change have been shown before with solid microcavities.

From an experimental point of view, the introduction of optical tweezers for immobilizing individual dielectric spheres by a tightly focused light beam has greatly improved the capability for making precise light-scattering measurements of spherical particles. With optical levitation, particles are held free of interfering obstacles so that they can be observed for long times. Highly transparent liquid drops in the 1-100 μm size range (smaller than the capillary length) are almost ideal spherical particles as their spherical shapes are determined by the surface tension but not gravity. Liquid droplets in this size range can easily be produced using aerosol generators in air or in a microfluidic chip and introduced into an optical trap.

The current proposal's idea was new and we were successful in achieving our aim of reporting a new experimental approach of observing scattering by the free space coupling of light between a fiber and the WGMs of an individual liquid droplet, optically trapped in another liquid, all inside a microfluidic channel. We also demonstrated that the sensitivity of the sensor can be increased by using a detection scheme in which the molecule to be detected absorbs at the laser wavelength used to excite the WG mode. If the wavelength of the WG mode overlaps the absorption spectrum of the probe, the cavity photon losses increase even more (lowering Q) and commensurately increase the sensor sensitivity.

We used oil droplets of diameter range (10-50μm) immersed in an immiscible low refractive index liquid instead of non-volatile milli-metric oil droplets suspended from the tip of a thin wire, our droplets are comparatively small and embedded in another host liquid inside a microfuidic chip. In our configuration evaporation was prevented and the shape and size of the droplet were maintained, leading to stable experimental conditions. Additionally, the introduction of optical tweezers inside a micrfouidic channel within a host medium was very convenient and successful in immobilizing

individual droplets and protecting them from external contaminants. Finally, we demonstrate to achieve successful integration of micro fields with droplet resonators. Incorporation of microfuidics is crucial in bio/chemical sensor development, as nearly all bio-sensing and much chemical-sensing analysis is performed in an aqueous environment. In our demonstration, droplet resonators are generated in a micrfouidic chip equipped with flow-focusing geometry and transported to another microfuidic chip where optical experiments are performed.

We introduce several variants of optofluidic microresonators based on active optical resonant cavities formed by free flowing the droplets in a flow focusing / T-junction geometries in a microfluidic chip and then confined in an optical trap. We showed that it is possible to achieve droplets of oil dispersed in water and trapped by light in an optical trap. We observed WGM modes in immersion oil/water droplets localized using optical tweezers and excited with a CW laser beam.

We observed WGMs scattering through free space coupling by using first multi mode fiber and then by using single mode fiber.

Observation of WGM in optically trapped microdroplet using Multimode fiber

The scattering spectrum exhibited multiple modes or peaks in intensity from 1560 nm to 1590 nm. Fig. 1 shows the five consecutive scattering spectra from an olive oil droplet. The peaks marked by black, red and green squares on each spectrum represent different WGM families. These mode structures can be seen clearly repeated in five consecutive spectra. Repeated wavelength scans indicate that the position of WGMs is almost stable. It shows that the size of the droplets in water is quite stable and do not change. The measured FSR is 13.3 nm and it agrees well with the calculated FSR value. We characterized the dependence of Q-factor on the size of benzyl benzoate droplets (Fig. 2). The Q-

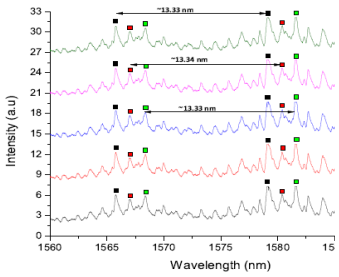


Fig.1 WGM modes observed in scattering mode. The two peaks represents two WGM modes and FSR

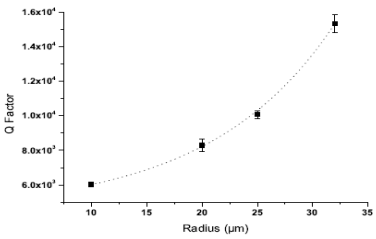


Fig. 2 Qfactor Vs Size dependent of the droplet

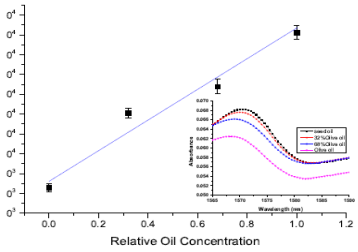


Fig. 3 Variation of Q-factor with relative oil concentration.

factors of four droplets of radius ranging from 10-32 µm immersed in 1 % SDS mixed water was measured. Increasing diameters resulted in increase of measured Q-factors (Fig. 2). In order to understand the sensing capability of these droplets, we used droplets of different chemical concentrations with different absorptions within same spectral range λ= 1560-1590nm). Since the droplets were generated in a microfluidic channel, it was very easy to generate same size of droplets (~40 µm). We observed coupling from the optically trapped droplets made of olive oil mixed to seed oil, with concentrations of 0%,32%,68% and 100% and measured the Q-factors of five droplets for each concentration which demonstrates the reproducibility of the measurements.
An almost linear relation was observed between average Q-factor and relative oil concentration, as shown in Fig.3. The maximum Q-factor observed for the pure olive oil droplet immersed in SDS water was 3.0×10^4 which is already limited by the adsorbed surfactant molecules at the interface as explained in the previous section. In this case, we are relying on absorption at the laser wavelength to affect the cavity Q. Note that, according to Fig. 3 insets, the absorption of pure olive oil at 1582 nm is 5% and of seed oil at 1571nm is 7%. The high Q-factor of 100% olive oil is attributed to the low absorption of the olive oil compared to the seed oil, within same wavelength range.

WGM scattering by coupling through single mode fiber

Optical whispering gallery modes (WGMs) were observed in scattering spectra recorded from oil-in-water emulsion droplets in a microfluidic channel. Droplets with diameters ranging between 15 and 50 µm were trapped by optical tweezers near the tip of a single mode fiber that enabled the excitation of

the WGMs using a tunable laser. Quality factors of the WGMs were observed to increase with droplet size. WGMs with Q-factors of more than 10^4 were observed for droplets with diameters around 45µm. In some cases, recorded WGMs drifted monotonically to the blue end of the spectrum due to droplet dissolution in the host liquid. Fluctuating spectral shifts to both blue and red ends of the spectrum were also observed. These were attributed to the presence of randomly diffusing particulate contaminants in the droplet liquid, indicating the potential of optically trapped droplet resonators for optical sensing applications.

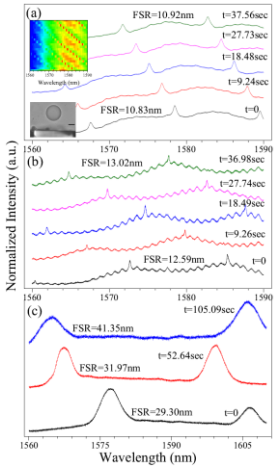


Fig.4 Measured consecutive scattering spectra of benzyle benzoate, optically trapped in water showing dissolution.

When the tunable IR laser beam was coupled efficiently to the rim of the droplet, WGMs were observed as peaks in the scattering spectra. Figure 4 shows scattering spectra recorded from exemplary BB droplets of three different sizes at room temperature (22.7°C). For all three droplets, a pattern of WGMs separated by FSR is clearly visible. During subsequent spectral scans, positions of individual WGMs typically displayed blue spectral shift, indicating partial dissolution of BB droplets in water. The observed dissolution of freshly prepared droplet was faster (blueshift of 20.6 nm within 37 s shown in Fig. 4(b)) in comparison to droplet stored for two days [blueshift of 6.8 nm within 38s shown in Fig. 4(a)]. This change in the dissolution rates of the droplets was attributed to the saturation of BB solution in DI water over time.

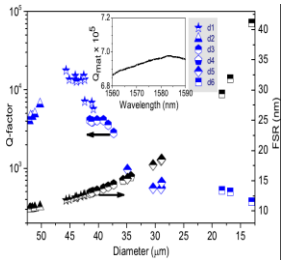


Fig.5. Measured Q-factors of WGMs of BB droplets optically trapped in water with diameters varying from 12 to 54 µm. Dashed line shows Qrad as a function of droplet diameter. Inset shows the measured spectral profile of Qmat of BB in the wavelength range of interest.

The dependence of the WGM Q-factor on the droplet size is shown in Fig. 5 for droplet diameters ranging between 12 and 54 µm. As shown in Fig. 3, the Q-factor has a tendency to increase with increasing droplet size. For the smallest studied droplet with initial diameter before dissolution d 18 µm (FSR = 29.3 nm), the measured FWHM was 4.5 nm, corresponding to a Q-factor of 5.2×10^2. At the other extreme, the narrowest measured FWHM was 0.08 nm for the droplet with d = 45µm (FSR=11.75 nm), indicating a Q-factor of 1.8×10^4. Figure 3 also shows Qrad values calculated for the parameter values used in our experiments. Qrad is obtained to be 8.1×10^3 and 5.5×10^7 for d=18µm and d=50µm droplets, respectively. We also performed absorption measurements on BB and calculated Q_{mat}, as shown in the inset in Fig. 5. At the operating wavelength of λ_0= 1575 nm, the calculated Q_{mat} for BB is 6.95×10^5. Hence, we conclude that for smaller droplets with d ~ 18 µm, the overall Q-factor is mainly determined by Qrad, whereas absorptive and scattering losses become more dominant for larger droplets. Losses due to absorption, scattering from particulate contaminants present in the droplet and host liquids, or perturbations in the size and shape of the droplet generally lead to shifts in the spectral position of WGMs and degradation of their Q-factor. An illustration of this phenomenon is provided in Fig. 6 where fluctuating spectral shifts of WGMs to both blue and red ends of the spectrum are observed in consecutive spectra recorded from a single trapped droplet. Unlike the monotonic spectral drift observed in slowly dissolving droplets (Fig. 4), spectral fluctuations shown in Fig. 6 are bi-directional, and their magnitude is significantly smaller. We estimated the spectral shifts of WGM resonant wavelength due to the presence of a particulate contaminant in the mode volume inside the droplet cavity from a simple geometric optics picture.

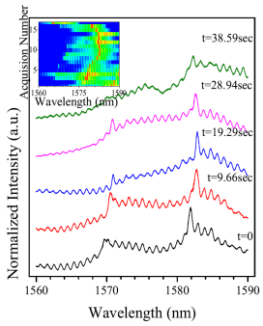


Fig.6 Consecutive WGM spectra of a single 44 µm diameter BB droplet optically trapped in water, showing sensitivity to minute perturbations of the cavity

We have demonstrated a new and simple approach for stable and efficient free-space optical coupling to WGMs of droplet resonators immobilized and positioned in an immiscible host liquid by using optical tweezers integrated with a microfluidic channel. Elastically scattered light from optically trapped emulsion droplets has been analyzed and Q-factors as high as 1.8×10^4 have been measured for droplets with a diameter of 45µm. We have also observed the dependence of the average Q-factor of the cavity WGMs on the droplet size for diameters between 18 and 50 µm. We also demonstrated that prolonged monitoring of WGM spectra of an individual optically trapped droplet revealed fluctuations in WGM spectral positions, thus hinting at the possibility of sensing minute perturbations of the cavity

and/or its environment in biological and chemical analysis. Further investigation of the optical properties of droplet-based microcavities can lead to the development of useful intracavity sensing schemes for monitoring biochemical processes occurring inside the droplets, a powerful tool for a lab-on-a-chip. This work is published in JOSA B.

Microfluidic chip fabrication

Microfluidic chips for single beam optical trapping were fabricated from PDMS elastomer by casting liquid PDMS precursor into a pre made mask. After solidification, the resulting PDMS block was peeled off the mold and the PDMS surface was activated together with a 150 µm thick microscope cover slip in oxygen-argon microwave-excited plasma (oxygen-argon 1:1, total pressure 500 mTorr, microwave power 50 W). Subsequently, the activated PDMS chip was pressed against the activated cover slip, thus sealing the chip permanently. The resulting chip featured one straight channel with square cross-section of 160×160 μm^2 and two perfectly aligned cylindrical slots for optical fibers in the middle. The liquid inlet and outlet of the channel were realized during PDMS casting with a wire inserted into the mold or after PDMS solidification by a hole-punch.

Humidity Sensing with SU-8 Optical Microdisc Resonators

In another study, we investigated integrated optical humidity sensors based on chips containing SU-8 polymer microdisks and waveguides fabricated by single-step UV photolithography. Sensing is achieved by recording spectral shifts of the whispering gallery modes (WGMs) of the microdisk microresonators. Between 0-1 % relative humidity (RH), an average spectral shift sensitivity of 108 pm/% RH is achieved, comparable to the highest values obtained using microresonators in the literature. Finite element modeling simulations were carried out to determine the dominant effect responsible for the resonance shift. The results show that the refractive index change is more important than the microresonator size change. The standard deviation in wavelength measurement is < 3 pm, indicating a limit of detection better than 0.03 % RH. These results suggest that optical sensor devices that contain integrated SU-8 microresonators and waveguides can be employed as easy-to-fabricate and sensitive humidity sensors.

A tunable telecom laser (1500-1620 nm) is coupled from an optical fiber to SU-8 waveguide using an end - face coupling as shown in Fig 7. When the wavelength of the light is in resonance with the SU-8 microdisc, the light couples to the whispering gallery modes (WGMs) of the microdisc (Fig 7, inset). Therefore, transmission dips are observed while the wavelength of the light is swept in a certain wavelength range (Fig 7(b)).

For sensitivity characterizations four different SU-8 microdisk resonator-based sensors are tested under various RH values from 0 % to 7 % (see Fig 7).Consecutive WGM spectra are recorded and spectral shifts of the WGM are analyzed with a Lorentzian tting code. These sensors have the same design geometry, but they are fabricated at different locations on the wafer. In Fig 8, the resonance shifts of Sensors 1 to 4 upon the RH change from 0 to 1 % are 130, 69, 83, and 151 pm, respectively (on average 108 pm). The different sensitivities are mainly attributed to local variations in the polymer structure in the regions where WGMs are located in a microdisk. This indicates a limit of detection better than 0.03 % RH, assuming linear dependence of the wavelength shift on RH between 0-1 % RH. Fig 9 depicts the response of our sensors during a complete cycle of adjustment of environmental RH. The RH is gradually varied from 0 % to 7 % and 150 then from 7 % back to 0 %. The zero level base line of the sensor is very well preserved, but a small deviation is visible between the increasing humidity and decreasing humidity cases, which leads to hysteresis.

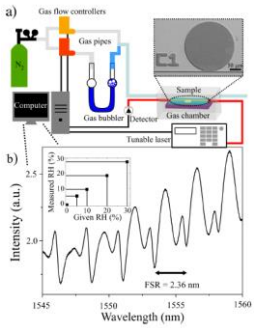


Fig 7. Experimental setup.

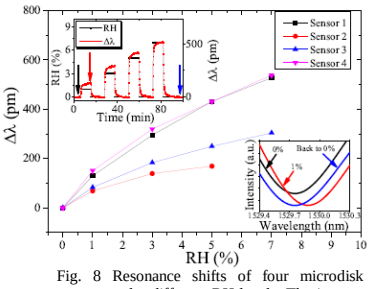


Fig. 8 Resonance shifts of four microdisk sensors under different RH levels. The inset at the top shows an exemplary raw data which belongs to Sensor 1

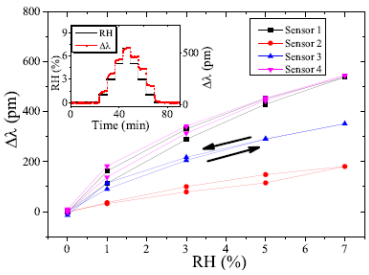


Fig 9. Hysteresis of the response curves obtained from four microdisk sensors.

Sensing with cylindrical micro-resonators

To measure the long term stability, in the conventional way, a tunable probe laser is scanned while continuously monitoring the frequency position of the WGMs. There are several factors influencing the WGM resonance frequency, such as thermal instability due to laser heating and coupling gap fluctuations caused by environmental factors. To avoid unwanted jittering between the WGM and the laser, the Pound-Drever-Hall (PDH) frequency locking technique is generally employed, where the laser source is tuned into resonance with the WGM to be tested and locked to the bottom of the resonance dip. The error signal from the lock-in loop can be used to monitor the WGM jittering noise. In another experiment, we are using this technique to lock tunable lasers to a cylindrical silica

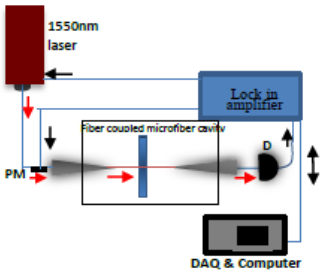


Fig. 9 PDH locking system.

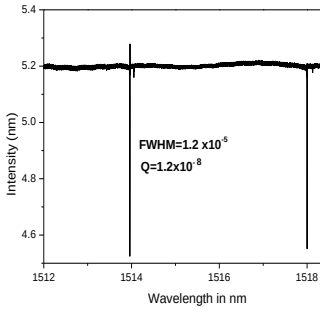


Fig 10. WGMs in transmission spectra from a bare fiber using tapered fiber.

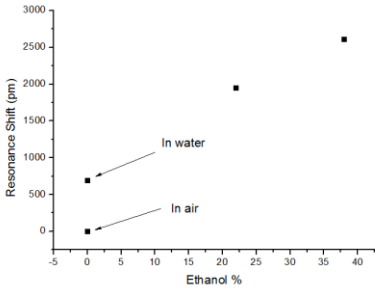


Fig 11. Resonance shifts of microfiber sensors under different % ethanol.

microresonator. The WGM resonator can be used as a feedback element to the laser, leading to a narrowing of the laser linewidth and/or improved stability. Fig 9 shows our scheme of the PDH locking system. The light from the tunable laser source (Santec) was used in the feedback loop for the PDH locking. The light was launched into the tapered fiber and the transmitted light after the microfiber-taper system was detected with a photodiode. Fig 10 shows the WGMs in transmission mode. The full width at half maxima (FWHM) of the WGM observed in transmitting signal is around 1.2×10^{-5} giving a Q-factor of the order of 10^8. FSR is observed to ~4.2 nm which corresponds to the used fiber diameter i.e. 125µm. We also tried to analyze the effect of ethanol, water and their mixture on the WGMs and as a preliminary result, we observed red shifts of the resonance modes in the presence of % ethanol-water mixture. We have got some good results which look interesting and within a few months it will be in a good shape for publication.

3. Communication and implementation of research findings *(Please report any other activities relating to the dissemination of research findings)*

I am writing a manuscript for the Journal Optics letters, which will be ready to submit in July 2015.

4.1. Publications *(Please list all publications arising from the work of the project over the last term in the indicated categories)*

Peer reviewed journals:

1. "Observation of Whispering Gallery Modes in Elastic Light Scattering from Microdroplets Optically Trapped in a Microfluidic Channel", **S. Anand**, M. Eryürek, Y. Karadağ, A. Erten, A. Serpengüzel, A. Jonáš, and A. Kiraz, J. Opt. Soc. Am. B 33 (7), 1349-1354 (2016). DOI: 10.1364/JOSAB.33.001349

2. Polymer Microdisk Microresonator Humidity Sensor, M. Eryurek, Z. Tasdemir, Y. Karadag, S. Anand*, Necmettin Kilinc, B. E. Alaca, and A. Kiraz. (Submitted to Sensor and Actuators, 2016) .

Non-peer reviewed journals:

1. Observation of Whispering Gallery Modes in Elastic Scattering from Optically Trapped Microdroplets in a Microfluidic Channel, S.Anand, M. Eryürek, Y. Karadag2 , A. Jonas, A. Serpengüzel , and A. Kiraz, Koç University, Department of Physics, Rumelifeneri Yolu, 34450, Sarıyer, Istanbul, Turkey

2. Efficient Optical fiber coupling to Whisper Gallery modes of optically manipulated emulsion microdroplets by **S.Anand**, Mustafa Eryürek, Y.Karadag, Ali Serpengüzel, and A. Kiraz at Department of Physics, Koç University, Rumelifeneri Yolu, Sariyer, 34450 Istanbul, Turkey, PIERS Proceedings, Prague, Czech Republic, July 6-9, 2015.

3. Hydrogen and Humidity Sensing Based on WGMs of Elastic Polymer Optical Microresonators by M. Eryurek, Y. Karadag, **S. Anand**, N. Kılınç, A. Kiraz at Department of Physics, Koç University, Rumelifeneri Yolu, Sariyer, 34450 Istanbul, Turkey, PIERS Proceedings, Prague, Czech Republic, July 6-9, 2015.

4. Humidity Sensing with SU-8 Optical Microdisk Resonators, by M. Eryürek, Y. Karadağ, **S. Anand**, A. Kiraz, Koç Üniversitesi Fizik Bölümü 34450 Sarıyer İstanbul, 2 Marmara Üniversitesi Fizik Bölümü 34722 Göztepe İstanbul, Presented at Fototonik 15, Ankara University, October 2015.

Invited reviews/editorials/other publications (e.g. reports): Nil

Published abstracts: 1

Invited Presentation:

1. Observation of Whispering Gallery Modes in Elastic Light Scattering from Microdroplets Optically Trapped in a Microfluidic Channel, oral presentation at EMN Meeting on Droplets 2016, 9-13 May, 2016, San Sebastian, Spain.

2. Biolasing from fluorescent proteins and live bacterial cells suspended in liquid droplet microcavities, Jonas Alexandr; Mehdi Aas, Yasin Karadag, Selen Manioglu, Suman Anand, David McGloin, Halil Bayraktar, Alper Kiraz, presented at 3rd EOS Conference on Optofluidics (EOSOF) , At WPC 2015, Germany June 22-24, 2015.

4.2. Conferences and Workshops *(Please give details of attendance at conferences and workshops)*

Conferences:

1. EMN Meeting on Droplets 2016, 9-13 May, 2016, San Sebastian, Spain.
2. COST MP1205 General Meeting and Conference, 11-13 April 2016, Koc University, Istanbul
3. FOTONİK 2015 at Ankara University, 18th October 2015.
4. Progress in Electromagnetics Research Symposium, PIERS 2015 in Prague, Czech Republic, 06-09 July 2015.
5. EOS Conferences at the World of Photonics Congress (WPC 2015), Munich, 22-24 June 2015.
6. FOTONİK 2014, 16. Ulusal Optik, Elektro-Optik ve Fotonik Çalıştayı, 5 Sep. 2014, Kocaeli.

Workshops:

1. Current trends in Biophotonics and BioMems, August 12, 2014, Istanbul Şehir University Güney Campus.

1. **Barriers to Research** *(Please list any issues that you have encountered that have hindered progress of your research activities.*

There is no hindrance in the progress of the project. Everything is fine.

2. **Project Effort per Work Packages** (*Please indicate the percentage of the outcome undertaken in each work package).*

Work Package	During reporting period (%)	Total (%)
WP 1	25	25
WP 2	50	50
WP 3	90	90
WP 4	95	95
WP 5	50	50

*: Boxes will expand as needed

3. **Project Cost** *(Please indicate the total amount of the cost undertaken in each cost category).*

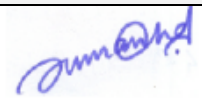
Cost Categories	During reporting period Jan 2015 to June 2015 (Turkish Liras)	Total (Turkish Liras)
Machinery and Equipment*		
Consumables*		
Travel		
Purchase of services*		

Living Allowance (July to December)		
Total		

* Please give details of purchased machinery& equipment, consumables and services in the following table.

No	Type of Product	Name/Model	Piece	Total Cost (Turkish Liras)
1	Machinery and Equipment	Desikator Vacumlu, Erkek konnector Optical components (Thorlabs)		
2	Consumables	Lamel, SU8, plastic, silkajel, Chemicals		
3	Purchase of services	nil		

Boxes will expand as needed

Name	Signature	Date
Researcher: Dr. Suman Anand		10/07/2016
Scientist in Charge Prof. Alper Kiraz		10/07/2016