REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)
07-06-2021

2. REPORT TYPE
Final Report

3. DATES COVERED (From - To)
8-Aug-2019 - 7-Mar-2021

4. TITLE AND SUBTITLE
Final Report: Chip-scale integrated ultrasensitive gyroscope based on liquid micro-resonators

5a. CONTRACT NUMBER
W911NF-19-1-0437

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
75338-PH-II.2

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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RPPR Final Report
as of 07-Jun-2021

Agency Code: 21XD

Proposal Number: 75338PHII **Agreement Number: W911NF-19-1-0437**

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DUNS Number: 007431505 EIN: 846000555
Report Date: 07-Jun-2021 Date Received: 07-Jun-2021
Final Report for Period Beginning 08-Aug-2019 and Ending 07-Mar-2021
Title: Chip-scale integrated ultrasensitive gyroscope based on liquid micro-resonators
Begin Performance Period: 08-Aug-2019 **End Performance Period:** 07-Mar-2021
Report Term: 0-Other
Submitted By: Juliet Gopinath Email: Juliet.Gopinath@colorado.edu
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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 0 **STEM Participants:** 1

Major Goals: To design and implement a chip-scale, integrated gyroscope based on a liquid droplet and that utilizes a nonlinear amplification of the Sagnac effect to enable a new level of performance, enabling accurate navigation in GPS-denied environments. This fundamental research project is focused on a novel gyroscope with excellent performance that will enable accurate navigation.

Accomplishments: Previously, we have successfully fabricated and demonstrated an optical liquid resonator as the first progress towards on chip scale liquid gyroscope. We have showed a quality (Q) factor of 4 × 104 for a glycerol resonator surrounded by a dodecane bath pumped at the 770 nm. Additional control over the droplet's size is achieved by using electrowetting which altered the chip's surface wettability. The spectral tuning of 1.44 nm exceeds the free spectral range (FSR) of 0.679 nm enabling various resonance mode to be selected. The spectral tuning is repeatable, and its precision is experimentally measured to be 5 pm, with simulations suggesting that the tuning speeds of 20 nm/s is possible. In this reporting period, we focused efforts of improving the Q-factor of the resonator to ensure that the power threshold needed to excite the nonlinear Kerr effect is within a few mW of power.

In the previous glycerol-dodecane liquid microresonator, radiation loss was analytically calculated to be the primary limiting factor in achieving Q factor 4 × 104. In efforts to alleviate this problem, we have chosen to use hexane as the non-polar liquid (surrounding liquid) due to its lower refractive index (n = 1.375) in comparison to dodecane (n = 1.42), raising the radiation limited Q-factor from 105 (for dodecane) to 1013 (for hexane). Hexane, unlike dodecane, is a more challenging to work with, which required multiple alterations to the system. Foremost, hexane features a lower vapor pressure, and the increased rate of evaporation caused the optical fiber to drift over time when within coupling distance to the droplet. This required the bath to be fully enclosed. Additionally, motorized stages are necessary as the fiber became impossible to optically distinguish as the diameter approaches 1-2 μm and its refractive index is closely matched to hexane. The experimental setup remains largely similar to the previously reported system. A summary of the system is as described. Light is coupled into the liquid microresonator using a tapered optical fiber. Both fiber and the chip are submerged within hexane bath. Once the fiber is position within coupling distance of the equator of the liquid droplet, the pump wavelength is swept to identify resonance which is represented by sharp decrease in transmission.

Q-factor measurements saw an improvement but varied from droplet to droplet with values ranging 104-106. In fact, we observed two distinct resonance modes with Q-factor of 104 and 106 at different pumping frequencies all within a single resonator (Fig. 1). To explain the discrepancy, it is important to first understand that the resonance supported within a Whispering Gallery Mode (WGM) resonator is characterized by the azimuthal (l), polar (m), and radial (q) quantum numbers. We simulated the resonance modes present within a 225 μm sized liquid droplet, matching the experimental conditions, by analytically calculating its position and the effective coupling conditions. The resonance frequency of a single mode family is dependent on the polarization, azimuthal, and radial mode numbers, whereas the polar mode number dictates the effective refractive index of the particular mode (Fig. 2). With the increased refractive index contrast, high polar order resonance modes are now supported within the droplet. However, only resonance modes which are phase matched with the light propagating within the tapered fiber (shown as the red dotted line) can be effectively excited. As a consequence of the large number of azimuthal modes supported, it becomes evident that the pumping frequency can selectively excite a fundamental mode or a high order polar mode (> 10). The measured fundamental mode shows a Q-factor of 3.5 × 106 which is slightly lower than the absorption limit at 107 (Fig. 3). In contrast, the high polar order mode measured a Q-factor of 104, which is observed to had light scattering from the droplet from a side imaging camera (Fig. 1). Thus, to achieve high Q-factors, the phase matching condition within a liquid droplet WGM resonator has to be carefully considered. The errors involved with dispensing a volume of droplet is typically beyond the requirements for phase matching, instead we decided to adjust the tapered fiber diameter accordingly to the droplet. Since tapered fibers are extremely fragile and has to be customized to the correct dimensions for submerging it in liquid, it was critical for us to create a system which could produce silica optical tapered fiber precisely and consistently.

Multiple tapering designs have been reported in literature and can be differentiated based on the type of heat source (CO2 laser, resistive heater, plasma). Plasma heat source has the advantage of being uniform and is largely adopted by commercial solutions but requires a complicated setup to account for humidity and other environmental factors. Instead, our design adopts a resistive heating element wrapped within a cylindrical ceramic insulator to confine the heat (Fig. 4). The design is simple to implement, with the main drawback being that the heating element oxidizes over time and requires to be replaced. Our initial test setup enabled us to reach temperatures of over 1000 ˚C with a power input of less than 200 W. The temperatures around the center of the ceramic insulation are measured to be the highest, reaching ~1200 ˚C with 147 W and dropping at a parabolic relationship further away (Fig. 5). The tapering process begins with placing a stripped fiber through the ceramic insulation. Then, the ceramic is heated up to the set temperature and the fiber is pulled outwards using two linear motor stages. Light is pass through the fiber and the transmission is collected throughout the process to identify the point when single mode is reached. This is due to the tapered fiber changing to a multi-mode state and back to a single mode state at the end. Once, all the other optical modes are coupled back into the fundamental mode, amplitude fluctuations observed in the transmission will come to a stop. Initial trials of the tapering system, showed that the uniform heating of the ceramic is able to satisfy the adiabatic heating condition, producing fibers which were > 95 % transmission. Fibers reaching single mode operation at 770 nm in air and had a consistent tapered profile along the fiber. Once the tapered fiber is fabricated, a holder is brought close to the fiber and a drop of UV curable epoxy is applied on either ends of the fiber. After curing the tapered fiber can be transferred over into the liquid bath setup.

With the completion of the fiber tapering system, progress to verify that the Q-factor resonance modes within the glycerol-hexane system can be selectively coupled to is expected to be completed within the near future. Noise analysis of the liquid microresonator system will be performed subsequently and prior to the gyroscopic measurement. Initial preparation for the liquid gyroscope has begun with photolithography mask for a test platform completed and microfabrication process currently being optimized. The optical setup to integrate the two propagation arms has been designed and the rotational stage for the liquid setup are ready to be assembled. In summary, we have demonstrated the initial concept of an on-chip high Q-factor liquid resonator. The platform offers a repeatable approach in handling liquid droplets without degrading the photon lifetime. With the high Q-factor, one of the main challenges with implementing the nonlinear optical gyroscope has been successfully addressed.

Training Opportunities: The project provided research opportunities for a graduate student, Wei Lim, and a senior research associate, Mo Zohrabi.

Results Dissemination: 1. W. Y. Lim, M. Zohrabi, J. Zhu, J. T. Gopinath and V. M. Bright, “Electrowetting-based tunable liquid droplet microresonator,” Presented at the IEEE MEMS Conference (2021).
2. W. Y. Lim, M. Zohrabi, J. Zhu, J. T. Gopinath and V. M. Bright, “Tunable droplet resonator based on electrowetting,” To be submitted to ACS Photonics (2021).

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

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Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

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Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
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Project Contribution:
National Academy Member: N

Participant Type: Other Professional
Participant: Mo Zohrabi
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 2021 IEEE 34th International Conference on Micro Electro Mechanical Systems (MEMS)
Date Received: 07-Jun-2021 Conference Date: 25-Jan-2021 Date Published: 15-Mar-2021
Conference Location: Gainesville, FL, USA
Paper Title: Electrowetting-Based Tunable Liquid Droplet Microresonator
Authors: WeiYang Lim, Mo Zohrabi, JianGang Zhu, Juliet T. Gopinath, Victor M. Bright
Acknowledged Federal Support: **Y**

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4
Scientific interchanges about project.

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ARO Final Report

June 6, 2021

Professors Juliet Gopinath and Victor Bright

University of Colorado Boulder

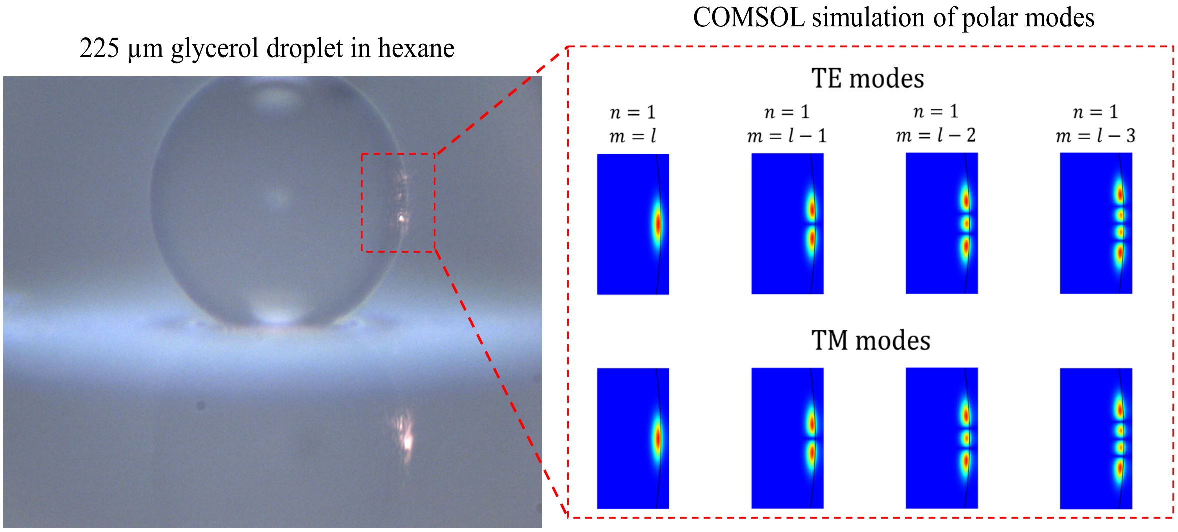

Fig. 1. (Left) Side image of the glycerol droplet submerged in a hexane bath. Light is coupled into the equator of the droplet using a tapered fiber and pumped in resonance with the low Q-factor (10^4) mode. Scattered light seen on the surface of the droplet at higher latitudes indicates that high order polar modes is excited and leaking out of the resonator. (Right) COMSOL simulation illustrating the propagation of higher order polar modes supported near the droplet surface.

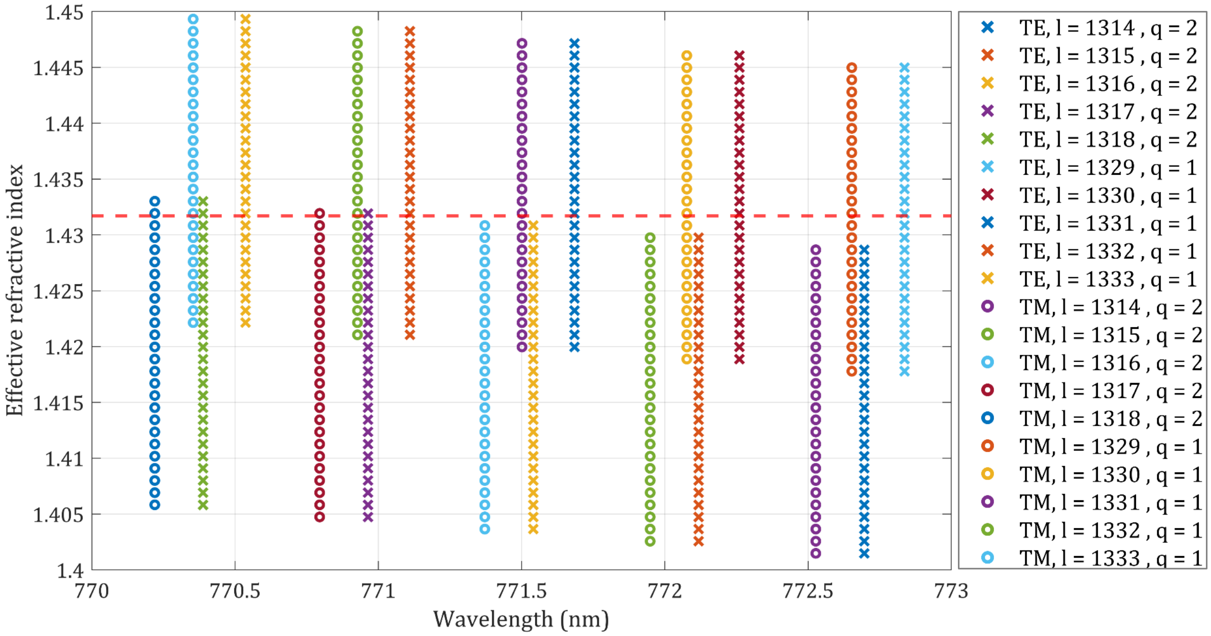

Fig. 2. Resonance mode present within a 225 µm whispering gallery mode resonator is analytically calculated (represented with circles and axes). Characteristics quantum numbers: azimuthal (*l*), polar (*m*), and radial (*q*) numbers describe the resonance. Each vertical set of resonance mode with the same wavelength represents modes of the same polarization, azimuthal, and radial number. Modes at the top represents the fundamental polar mode and increases going down. The dashed red line indicates the effective refractive index of the tapered fiber coupled to the droplet. Modes with similar refractive index as the fiber satisfies the phase matching condition, enable the efficient coupling of light. Resonance modes around 771 nm highlights both fundamental and a high order polar mode can be simultaneous excited. Due leaky modes at the higher polar numbers, it is critical to account for the phase matching condition to achieve the highest Q-factors within a liquid resonator.

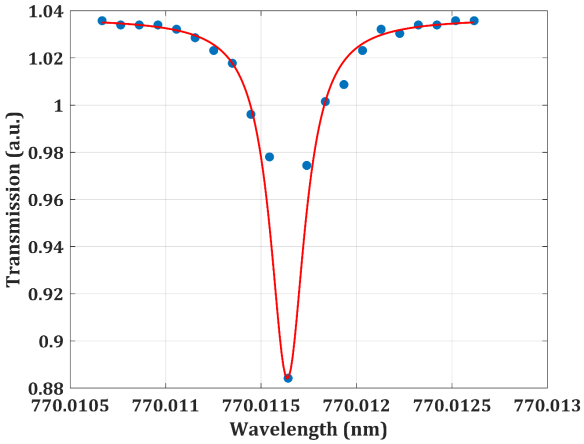

Fig. 3. Unloaded Q-factor of the fundamental resonance mode within the glycerol-hexane droplet measured to be 10^6 using a Lorentzian curve fit.

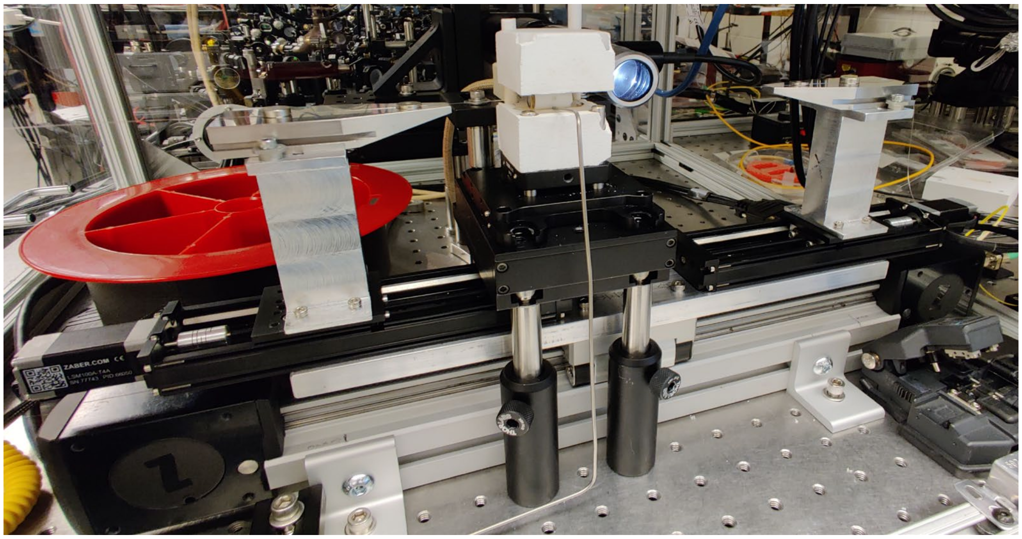

Fig. 4. Fiber tapering system with an alumina ceramic furnace in the center cladded by two insulation layers. Thermocouple is used to measure the temperature of the ceramic. Once the furnace is heated up to the set temperature, the two linear motor stages are used to pull the fiber to the desired diameter. The tapered fiber is then moved to the side where it can be inspected by a high magnification microscope and transferred onto a holder.

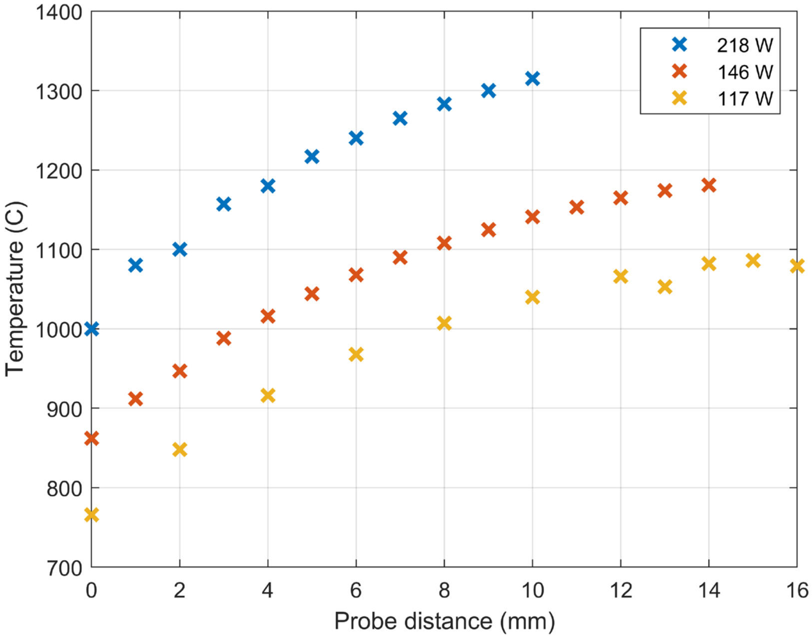

Fig. 5. Temperature profile of the ceramic heater. For tapering silica fiber, the temperature at the center of the ceramic heater has to reach the glass transition temperature of silica (1200 ˚C). Center of the ceramic was ~ 15 mm away from the probe.