ELECTROWETTING-BASED TUNABLE LIQUID DROPLET MICRORESONATOR

WeiYang Lim,[1] Mo Zohrabi,[2] JianGang Zhu,[2] Juliet T. Gopinath,[2,3] and Victor M. Bright[1]*
[1]Paul M. Rady Dept. of Mechanical Engineering, University of Colorado, Boulder, CO, USA
[2]Dept. of Electrical, Computer, and Energy Engineering, University of Colorado, Boulder, CO, USA
[2]Dept. of Physics, University of Colorado, Boulder, CO, USA

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ABSTRACT
A tunable liquid whispering gallery mode (WGM) resonator based on the electrowetting principle is presented. The liquid resonator consists of a glycerol droplet submerged within an immiscible liquid (dodecane/hexane) bath. The diameter of the droplet is electrically tuned using the electrowetting effect, resulting in a redshift in optical resonance frequency. By applying 35 V, a maximum spectral tuning of 1.44 nm ± 5 pm is achieved. The tuning range achieved is twice the free spectral range (FSR) of the resonator, 0.679 nm. The Q-factor of the resonator with a glycerol droplet in hexane liquid system is measured to be 3.5 × 10^6. This work represents a new on-chip design, fabricated using standard microfabrication techniques, for future physical and biochemical sensing applications.

KEYWORDS
Tunable resonator, liquid resonator, whispering gallery mode

INTRODUCTION
In a whispering gallery mode (WGM) optical microresonators, light is guided by continuous total internal reflection around the surface of the resonator. Physical perturbations to the resonator can be detected with extreme sensitivity due to the long photon lifetime within the cavity [1]. As a result, WGM resonators have seen a surge in interest in sensing applications ranging from gyroscopes [2] to biosensors [3]. Within a solid microresonator, only specified families of resonance modes are permitted to propagate. This is dictated by the final dimensions of the resonator. Tunability is a highly desirable characteristic for applications including microlasers [4], optical filters [5], and optical switches [6], but is especially challenging in smaller resonators. To fully access any resonance mode across the optical wavelength, a tuning range of >1 nm is required for resonators of radius < 50 µm to exceed the free spectrum range (FSR). While numerous tuning techniques have been proposed (mechanical strain [7], birefringence [8], and thermo-optic effect [9]), most suffer from the need of a complex external setup, low Q-factor, or a dependency on the surrounding environment for heat dissipation. An attractive alternative is offered by electrically tuning the flexible liquid interface of a droplet microresonator. This results in a large tuning range, while maintaining a high Q-factor (>10^6).

Liquid resonators remain largely unexplored in comparison to solid resonators. A liquid resonator possesses several key advantages over a conventional solid resonator. Foremost, the liquid interface is formed through a balance of interfacial surface tension and internal pressure. Surface tension continuously minimizes the droplet's surface area, thus creating an atomically smooth interface (~few Angstroms) at rest or in an actuated state [10]. Without the need of additional processing, issues with fabrication defects common in solid resonators are avoided. Studies have suggested the Q-factor is only bound by material absorption and radiation losses [11]. Large tuning range can also be achieved with the flexible liquid interface at kHz speeds in micro-sized droplets. The combination of these properties makes liquid resonators an ideal choice for dynamic tuning applications.

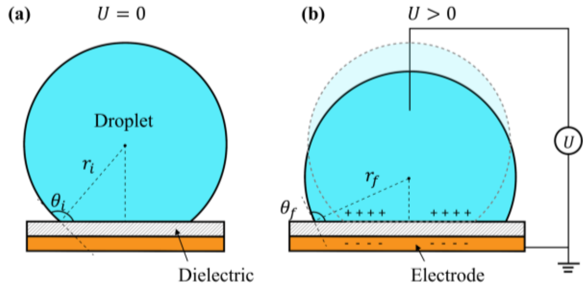
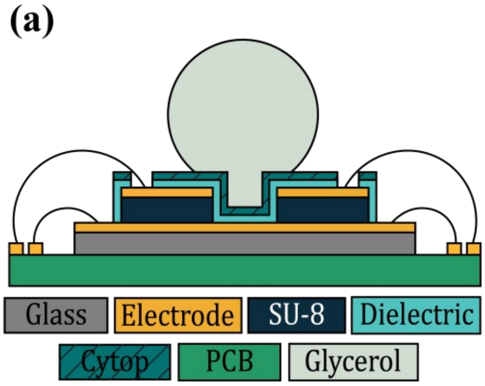


Figure 1: (a) Geometry of a liquid droplet on a dielectric solid surface with an initial contact angle of θ_i and a radius of r_i. (b) Charge buildup on the dielectric surface upon the application of an electric potential. This leads to a decrease in contact angle and an expansion of equatorial radius.

Despites the many advantages, liquid resonators face challenges that restrict their widespread adoption. These include sensitivity to environmental humidity, optocapillary noise, optoacoustic oscillations, and difficulty in handling. In this work, we introduce a tunable on-chip liquid microresonator consisting of a liquid droplet submerged within an immiscible liquid bath (dodecane or hexane). The immiscible liquid surrounding suppresses humidity and vibrational effects when compared to an air environment. Standard microfabrication techniques are used to fabricate the device to enable future scalability and easy integration. The resonance frequency of the microresonator is fully tunable using the electrowetting effect, which causes an expansion in the diameter of the droplet and an increase in the optical path length.

ELECTROWETTING THEORY
The electrowetting effect is the change in wettability of a surface through an applied electric field. The design of an electrowetting device is analogous to parallel plate capacitor. Voltage is applied to a polar liquid and an electrode separated by a dielectric material to prevent unwanted electrochemistry. As electrical charges build up



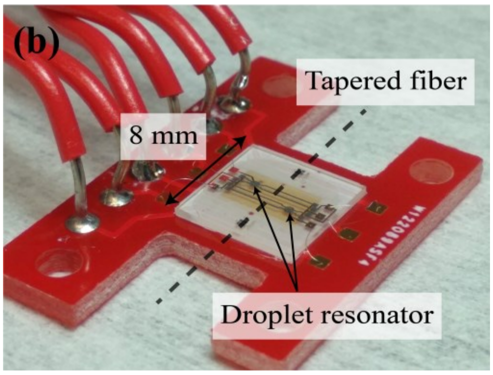


Figure 2: (a) Cross-sectional view of the liquid microresonator chip (b) Assembled device with electrical connections bonded to the external PCB pads. SU-8 wells are situated off-center to allow tapered fiber to couple to each droplet.

along one side of the dielectric, ions within the liquid accumulate on the opposing side to form an electrical double layer (Figure 1). The increase in surface charge density along the dielectric layer leads to an effective reduction in the solid-liquid interfacial surface tension. As a result, the liquid droplet spreads along the surface reaching a new contact angle which can be described through the Lippmann-Young equation:

$$cos(\theta_f) = cos(\theta_i) + \frac{\varepsilon_o \varepsilon_r}{2d\gamma_{lf}} U^2 \qquad (1)$$

where θ_f represents the final contact angle of the droplet after actuation, θ_i is the initial contact angle, ε_o is the permittivity of free space, ε_r is the dielectric constant of the insulator, d is the dielectric thickness, γ_{lf} is the interfacial surface tension between the liquid-surrounding fluid, and U is the applied voltage. With an increase in equatorial diameter, the resonance optical frequency will be redshifted.

DEVICE FABRICATION AND EXPERIMENTAL SETUP

The tunable electrowetting based microresonator is fabricated using standard microfabrication techniques. The fabrication process begins with the patterning of 300 nm of Au ground electrode on a fused silica wafer. A 12.2 µm SU-8 layer is then patterned on top of the ground electrode to form a "well" shape to enable a continuous annular electrode design on top of the SU-8; this also confines the droplet to the center. Next, a 300 nm thick layer of Al is deposited on top of the SU-8 layer as the actuating electrode. A layer of dielectric material (Parylene HT) is uniformly deposited using a physical vapor deposition process before individual chips are diced and released. The chips are then coated with a uniform layer of hydrophobic coating (Cytop) and epoxy bonded to a custom designed printed circuit board (PCB). Finally, the wirebonding pads on the chip are exposed and wirebonded to the PCB for external electrical connections. A glycerol droplet (refractive index n = 1.47) is then dispensed on top of the chip using a glass micropipette. Cross-sectional drawing and the final assembled device are illustrated in Figure 2.

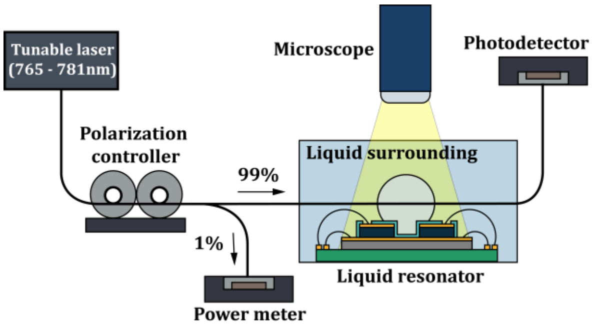


Figure 3: Schematic of the liquid microresonator experimental setup. Light is coupled into the liquid droplet microresonator through a tapered fiber. The tunable laser is swept across a spectral range (770-775 nm). A fast photodetector measures power in the transmission and a power meter monitors the input power.

The optical setup (Figure 3) uses a tunable, single-frequency, continuous wave (765-781 nm Newport TLB 6712) laser. Input power into the resonator is monitored continuously by splitting one percent of the power prior to the resonator. The transmission signal is recorded on a fast photodetector (Newport 1801-FC) with a bandwidth of 125 MHz. Light is coupled into the microresonator using a tapered single mode optical fiber (Thorlabs SM600). The tapered fiber is made using a heat-and pull-method which yields a fiber diameter of ~2 µm. To immerse the droplet in a surrounding liquid, the microresonator chip is secured inside of a liquid bath holder. The surrounding liquid either dodecane (n = 1.42) or hexane (n = 1.375) is slowly dispensed into the bath holder until the glycerol droplet is completely submerged. The diameter and contact angle of the droplet is measured using a side imaging camera with a 10x objective aligned horizontally to the droplet. Figure 4 shows a glycerol droplet inside of a dodecane bath with a diameter of 191 µm and an initial contact angle of 145.8± 1.8º.

TUNABLE RESONATOR RESULTS

By scanning the tunable laser across a spectrum, resonance within the liquid droplet is detected by monitoring for a sudden drop in transmission signal. An external function generator is used to tune the laser wavelength from 770 to 775 nm at a rate of 0.25 nm/s. Resonance peaks are fitted with a Lorentzian curve to quantify the Q-factor. For the glycerol droplet within the dodecane bath liquid system, a Q-factor of 4×10^4 is measured. Calculating the theoretical

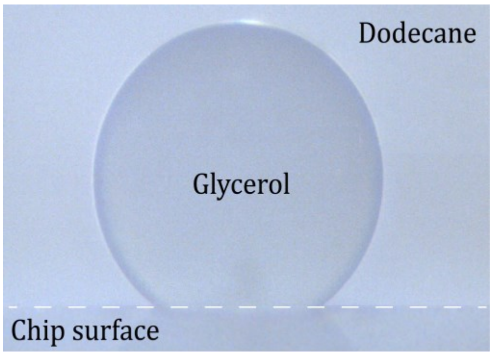


Figure 4: Side view image of a glycerol liquid droplet on the electrowetting chip surrounded by a dodecane bath. Dashed line indicates the surface of the chip. Initial contact angle is measured at 145.8˚ with a diameter of 191 µm.

Q-factor limits from the Maxwell's equation [12], shows that the current liquid system is radiation limited with a radiation Q-factor of 2×10^5 and an absorption Q-factor of ~2×10^7. The low refractive index contrast between the droplet and its surrounding liquid (Δn = 0.05) is attributed to the poor confinement of light. Instead, a non-polar liquid with a large refractive index contrast with glycerol, such as hexane (Δn = 0.095) can be used in place of dodecane, improving the theoretical radiation Q-factor to 7×10^{13}. In addition, the phase matching condition between the refractive index of the fiber and the resonator resonance mode is optimized to efficiently excite the fundamental order modes. This enables coupling to lower polar order mode numbers where the light is confined within the equatorial plane. With the glycerol droplet in hexane liquid system, two orders of magnitude of improvement in the Q-factor of 3.5×10^6 is achieved (Figure 5).

The design of a liquid droplet submerged within a surrounding liquid medium instead of air overcomes the sensitivity to environmental factors. Initial measurements of the glycerol droplet in air show resonance frequency drifting over time. Since glycerol is hygroscopic, the moisture in the air is absorbed, leading to an expansion in the droplet radius. Both vibrations and humidity effects were observed to be significantly suppressed within the liquid bath. The surrounding immiscible liquid also enhances the initial contact angle of the glycerol droplet from ~100˚ in air to 145.8˚ in dodecane. This increases the curvature of the liquid interface providing for better light confinement and enabling a larger choice of liquid combinations that can be used for biological and chemical sensing application.

The optical resonance frequency in the liquid microresonator is tunable by applying an electrical potential between the Au and Al electrodes. A sinusoidal 3kHz voltage function with a root mean square (RMS) voltage is applied in intervals of 5 V from 0 to 35 V. Figure 6 demonstrates the transmission spectra collected using the photodetector at each voltage step. Throughout the scan, two distinct resonance peaks are observed to be repeated across the spectrum starting at 771 nm at 0 V actuation. The two resonance modes are identified by matching their spectral position against the analytical solution calculated using an explicit asymptotic formula as described by Lam et al. [13]. Using the material parameters of the liquids

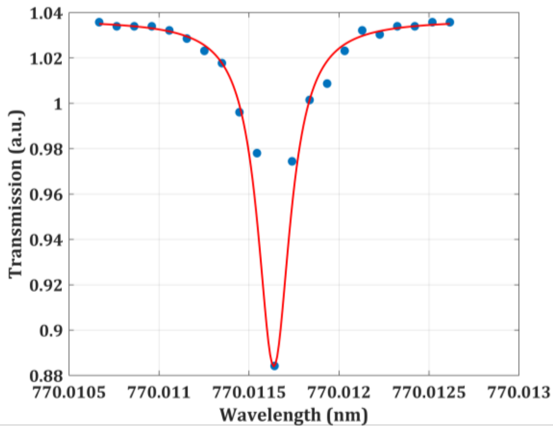


Figure 5: A Q-factor of 3.5×10^6 is measured by fitting a Lorentzian function to the resonance peak of the glycerol droplet in hexane system.

($n_{glycerol}$ = 1.47, $n_{dodecane}$ = 1.42) and the measured droplet radius of 95.5 µm, the predicted spectrum is found to match well with the experimentally observed results with errors of less than 10 pm in spectral position. The first resonance peak is identified as resonance with an azimuthal mode number m = 1128 and a radial mode number n = 1. The two peaks correspond to resonance with different polarization, with transverse magnetic (TM) followed by transverse electric (TE). The free spectral range between the successive resonance peaks is measured at 0.679 nm.

As increasing voltages are applied to the microresonator chip, the resonance frequency is shifted towards longer wavelengths. This behavior corresponds to electrowetting theory, which predicts an expansion of the droplet diameter with voltage and a redshift in the optical resonance frequency. At a voltage of 35 V, a maximum spectral tuning of 1.44 nm is observed. Repeated scans demonstrate that the resonance shifts are consistent with a standard deviation of 5 pm between successive cycles. With the tuning range of the resonator exceeding its FSR, the resonance can be tuned to match any optical frequency.

CONCLUSION

In summary, we have demonstrated a tunable liquid microresonator. The device is fabricated using microfabrication methods and mitigates the sensitivity to environmental conditions by operating within an immiscible surrounding liquid. This represents a stable and reproducible platform for future liquid resonator applications. Through the electrowetting effect, the geometry of the droplet is controlled using an applied electric field. Spectral tuning in the glycerol-dodecane liquid system is shown to generate a tuning range of 1.44 nm with 35 V, exceeding the resonator's FSR (0.679 nm). Alternatively, a glycerol-hexane system is used to achieve a Q factor of 3.5×10^6, closer to the absorption limits of these liquids.

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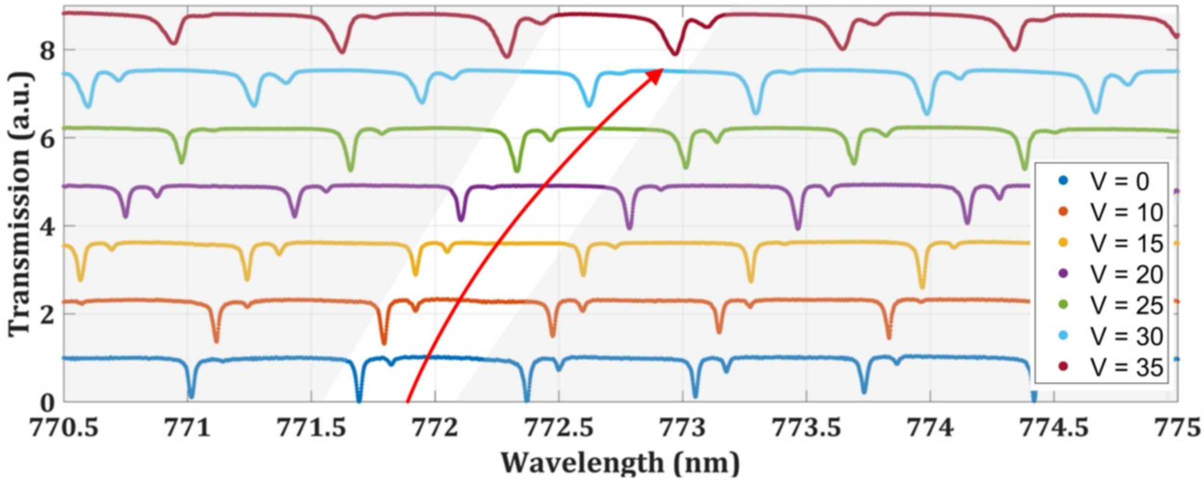

Figure 6: Recorded transmission signal as a function of actuating voltage on a glycerol droplet surrounded by dodecane. The two peaks repeated across the spectra correspond to resonance modes of TM and TE polarization. When a voltage function is applied, the resonance frequency redshifts in agreement with the prediction through the electrowetting equation. Free spectral range is measured at 0.679 nm.

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