# High Quality Factor Gyroscope Resonators Formed with Blowtorch Reflow Molding

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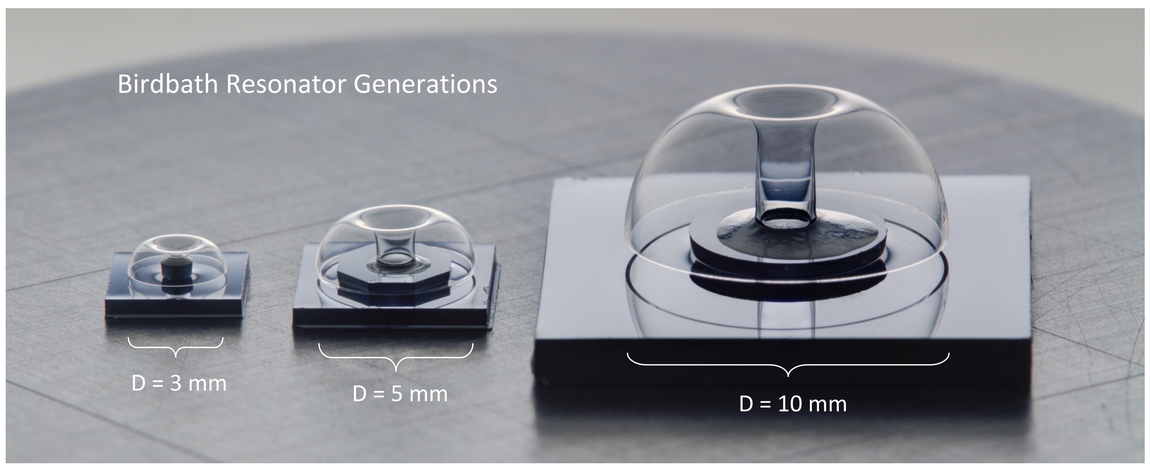
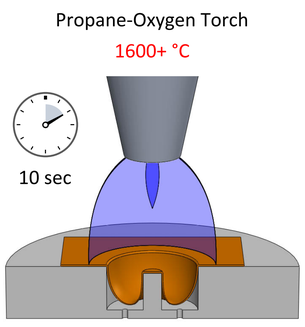
## Motivation

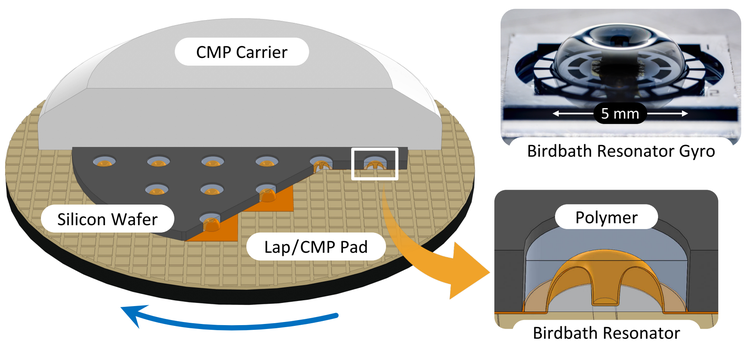
- ✧ Create high-precision micro-gyroscope for dead reckoning navigation.
- ✧ Use exotic high-$Q$ materials to create complex 3D structures not possible with conventional microfabrication.
- ✧ Form resonators with thermal reflow using a blowtorch in only 10 seconds.
- ✧ Achieve long ring-down time constant ($\tau$) to lower bias instability (B), reducing measurement drift. → $B \propto 1/\tau$ [1], $Q = \pi \tau f$




## Fabrication Process




Vacuum form fused silica in machined graphite mold




Lap and CMP to remove bulk substrate and polish rim

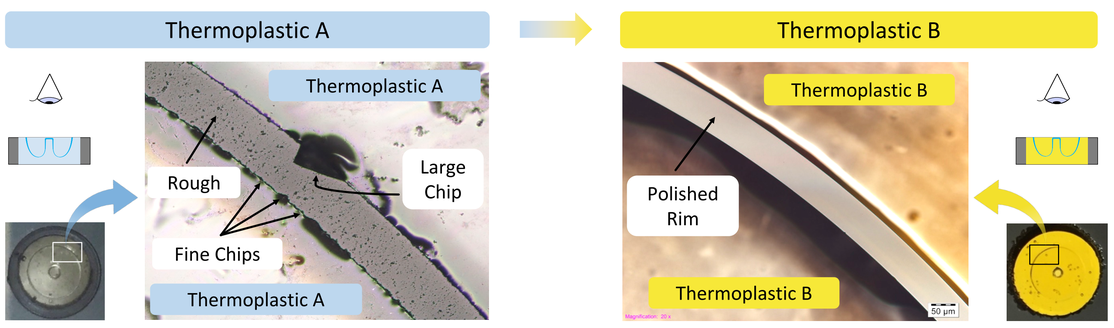



Birdbath Resonator Gyro

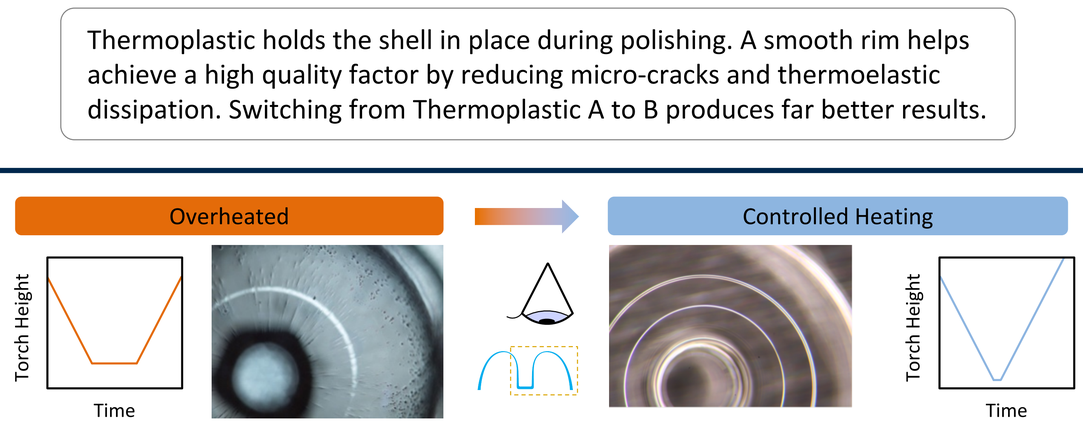



Birdbath Resonator

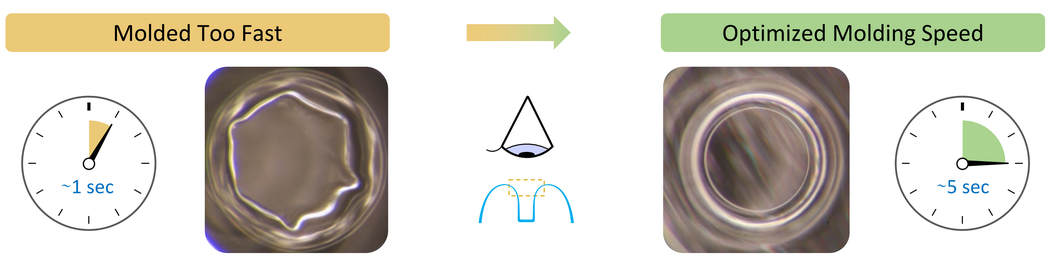
## Overcoming Unique Fabrication Challenges




Thermoplastic holds the shell in place during polishing. A smooth rim helps achieve a high quality factor by reducing micro-cracks and thermoelastic dissipation. Switching from Thermoplastic A to B produces far better results.



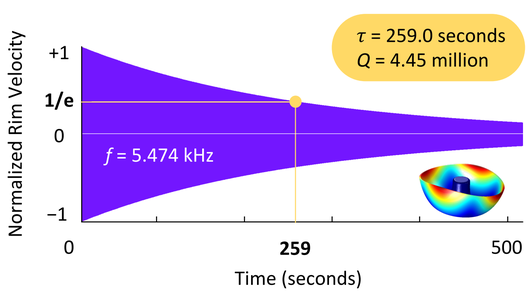

A rough surface results in low $Q$, likely due to surface losses.
Optimizing the temperature profile during molding improves surface quality.




A non-circular stem results in low $Q$, likely due to increased anchor loss.
Fused silica is viscous during reflow; molding slowly produces a circular anchor.

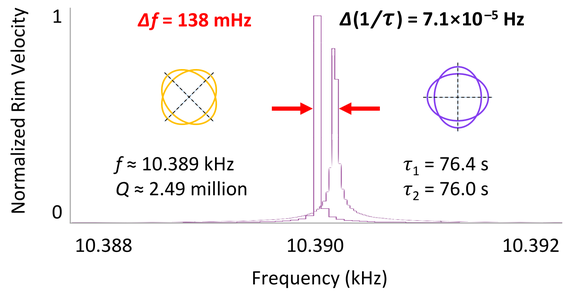
## Results and Discussion

Long Ring-Down (10 mm Diameter BB)



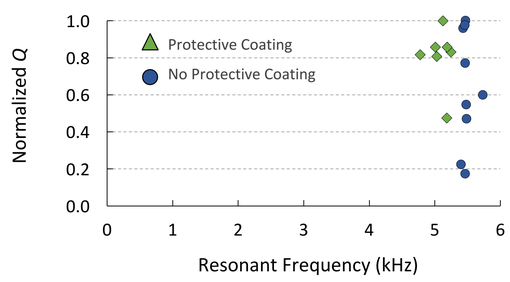

In 2013 our longest ring-down was 8 seconds. Fabrication improvements led to a >32× increase, paving the way to high-precision micro-gyros.

Low Frequency Split (5 mm Diameter BB)



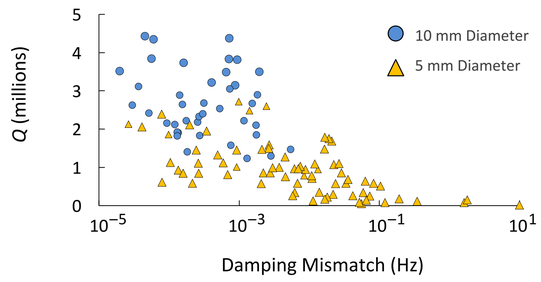

Matched wine-glass mode frequencies maximize gyro resolution by promoting drive and sense mode coupling. Some electrical compensation is also possible.

Repeatable Performance



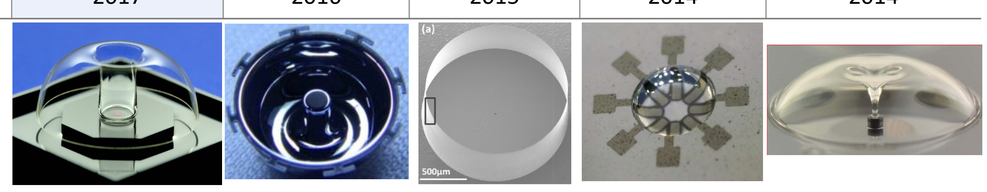

Resonant frequency is consistent. The addition of a protective coating before lapping and polishing improves quality factor repeatability.

$Q$ vs Damping Mismatch $\left(\frac{1}{\tau_1} - \frac{1}{\tau_2}\right)$




There is a strong correlation between damping mismatch and quality factor. This indicates the importance of symmetry, both in structure and surface condition.

| | This work [2] | Li et al. [3] | Najar et al. [4] | Vafanejad & Kim [5] | Senkal et al. [6] |
|---|---|---|---|---|---|
| **Ring-Down (s)** | 259.0 | 1.7 | 4.32 | 23.0 | 3.18 |
| **Quality Factor** | 4.45 million | 12,558 | 313,100 | 8.74 million | 1.05 million |
| **Freq. (kHz)** | 5.474 | 10.3 | 23 | 126 | 105 |
| **Material** | Fused Silica | Fused Silica | Polycrystalline Diamond | Silicon Nitride | Fused Silica |
| **Year** | 2017 | 2016 | 2015 | 2014 | 2014 |




## Conclusions

- ✧ Achieved longest reported ring-down time for micro-shell resonator (259 s).
- ✧ Long $\tau$ enables low predicted bias instability of $10^{-2}$ °/hr (navigation grade).
- ✧ Produced low as-fabricated frequency split and damping mismatch.
- ✧ Enabled repeatable quality factor and targeted resonant frequency.
- ✧ Achieved high quality factor resonators by optimizing rim polishing, blowtorch motion, and molding speed.
- ✧ Blowtorch molding is rapid and versatile, creates 3D structures with exotic materials not possible with conventional micromachining.

## Acknowledgements

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## References

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