

# Microfluidic Synthesis of Piezoelectric-Magnetic Composite Microbeads for Wireless Neural Stimulation

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## Summary:

This work presents a microfluidic approach for manufacturing piezoelectric–magnetic composite microbeads for wireless neural stimulation. By integrating particle-laden droplet generation with UV polymerization, uniform functional microbeads with a diameter of 100  $\mu\text{m}$  are produced at a generation frequency of about 20 Hz. The system combines magnetic steering and ultrasound-triggered piezoelectric response, enabling remotely controlled actuation. The approach offers a scalable route toward multifunctional microbead-based systems for bioelectronic applications.

**Keywords:** droplet microfluidics, composite beads, piezoelectric materials, magnetic particles, neural stimulation

## Background, Motivation and Objective

Wireless neural stimulation has emerged as a promising alternative to conventional electrode-based interfaces, offering reduced invasiveness and improved spatial control compared to conventional tethered electrode-based systems [1]. Although the piezoelectric effect is well known, recent studies have shown that piezoelectric nanomaterials can transduce ultrasound-induced mechanical energy into electrical signals sufficient to stimulate neuronal activity. [2]. Integrating magnetic components in such materials further enables remote positioning and guidance of such stimulators [3]. However, such approaches typically rely on high particle concentration suspensions (e.g., in the mg/mL range) to achieve a reliable and sufficiently strong response to external fields such as ultrasound, due to their stochastic distribution and activation at the microscale.

Droplet microfluidic technologies enable deterministic control over droplet generation and precise encapsulation of functional materials, providing a scalable route to engineer uniform, multifunctional micro-components with well-defined composition and architecture [4], [5]. In parallel, our previous work on particle-laden inks demonstrated that particle concentration strongly influences droplet formation through coupled effects on viscosity and interfacial tension, enabling controlled generation of uniform microbeads [6]

Building on this foundation, the objective of this work is to develop a microfluidic platform for

producing composite microbeads containing both piezoelectric ( $\text{BaTiO}_3$ , 200 nm) and magnetic ( $\text{Fe}_3\text{O}_4$ , 100 nm) particles, targeting applications in wireless neural stimulation.

## Description of the New Method or System

We propose a microfluidic-based fabrication approach for generating polymerizable droplets encapsulating multiple functional particles. An acrylate-based resin (PEGDA 250) containing 5 wt% photoinitiator (DMPA) is loaded with 20 wt% piezoelectric particles and 5 wt% magnetic nanoparticles, followed by ultrasonication for 30 seconds to ensure homogeneous dispersion. The resulting suspension is then processed using a flow-focusing PDMS microfluidic device.

The system leverages insights from particle-laden droplet dynamics: the particle concentration modifies both viscosity and interfacial tension, which together determine the capillary number and govern droplet formation regimes [6]. By tuning flow conditions, stable dripping regimes are achieved, producing highly uniform droplets.

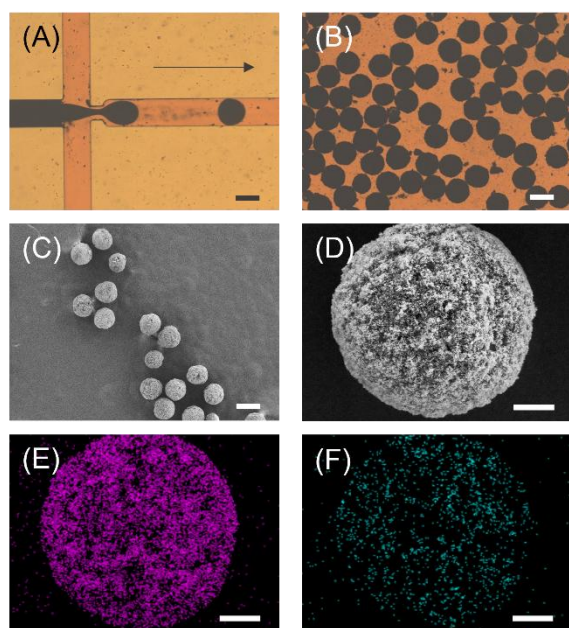
These droplets are collected in a glass vial together with the continuous liquid phase, and then polymerized using UV irradiation (365 nm, 114 mW/cm<sup>2</sup>, exposure time about 2 min) to form solid composite beads. The resulting particles combine magnetic responsiveness for spatial control and piezoelectric functionality for ultrasound-triggered electrical output. Compared to surface-coating approaches [3], this method allows the incorporation of functional particles

throughout the bead volume, resulting in higher particle loading per bead and potentially leading to an enhanced response under stimulation.

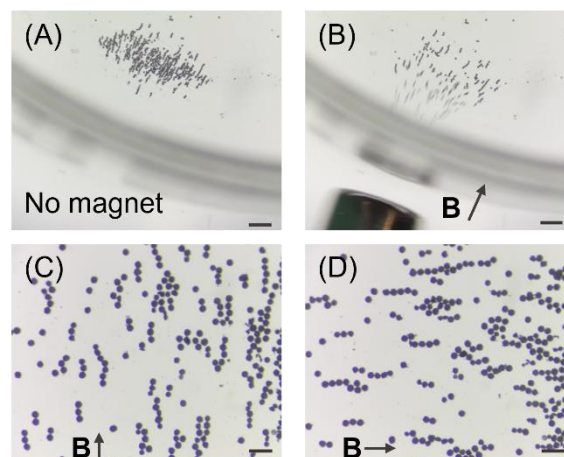
## Results

Microfluidic processing enabled the generation of monodisperse composite droplets that were subsequently solidified into spherical microbeads, as shown in Fig. 1 (A, B). Consistent with prior findings, stable dripping regimes produced highly uniform bead sizes, while increased particle loading influenced droplet size and formation behavior. In Fig. 1 (C–F), scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) confirm homogeneous distribution of  $\text{BaTiO}_3$  and  $\text{Fe}_3\text{O}_4$  nanoparticles on the bead surface.

The beads exhibit magnetic responsiveness, allowing controlled motion and positioning under external magnetic fields generated by five permanent magnets (5 mm in diameter), including translation in Fig. 2 (A, B) and rotation in Fig. 2 (C, D). While piezoelectric actuation has not yet been experimentally characterized, the incorporation of piezoelectric nanoparticles is designed to enable ultrasound-induced electrical responses. Together, these features establish a foundation for future development of localized, wireless neural stimulation systems.



**Fig. 1.** Microfluidic synthesis of composite microbeads encapsulating 20 wt% piezoelectric ( $\text{BaTiO}_3$ ) and 5 wt% magnetic ( $\text{Fe}_3\text{O}_4$ ) particles. (A) Optical image of the microfluidic junction illustrating droplet generation in the dripping regime. (B) Droplets collected prior to UV curing. (C–D) SEM images of the solidified beads. (E, F) Elemental mapping indicating the spatial distribution of barium and iron on the bead surface. Scale bars: (A–C) 100  $\mu\text{m}$ , (D–F) 20  $\mu\text{m}$ .



**Fig. 2.** Magnetic actuation of composite microbeads (approximately 300 beads) in water. (A, B) Beads are attracted toward a permanent magnet placed outside a glass vial. (C, D) Beads rotate in response to the rotation of a nearby permanent magnet. Arrows next to **B** indicate the direction of the applied magnetic field. Scale bars: (A, B) 1 mm; (C, D) 500  $\mu\text{m}$ .

## Conclusion

This study demonstrates a microfluidic strategy for fabricating multifunctional piezoelectric–magnetic composite beads. By combining controlled droplet generation with particle-laden ink design, the approach enables precise tuning of bead size, composition, and functionality.

The integration of magnetic guidance and piezoelectric activation offers a promising pathway toward wireless, minimally invasive neural interfaces. More broadly, this work establishes a foundation for microfluidic-based additive manufacturing of functional micro-objects with applications in bioelectronics and smart materials. The approach enables continuous production with high yield and uniformity at a throughput of  $\sim 20$  Hz per channel, and is inherently scalable via parallelization of microfluidic modules to further increase production capacity.

## Acknowledgements

Authors acknowledge funding from the Swiss National Science Foundation (SNSF, grant number: 219165). We thank Prof. Véronique Michaud and Jean-Baptiste Desbrest for their  $\text{BaTiO}_3$  particles.

## References

- [1] I. Bok *et al.*, “Wireless agents for brain recording and stimulation modalities,” *Bioelectron Med*, vol. 9, no. 1, p. 20, Sep. 2023, doi: 10.1186/s42234-023-00122-5.
- [2] A. Cafarelli *et al.*, “Piezoelectric Nanomaterials Activated by Ultrasound: The Pathway from Discovery to Future Clinical Adoption,” *ACS Nano*, vol. 15, no. 7, pp. 11066–11086, Jul. 2021, doi: 10.1021/acsnano.1c03087.

- [3] M. Han *et al.*, “Janus microparticles-based targeted and spatially-controlled piezoelectric neural stimulation via low-intensity focused ultrasound,” *Nat Commun*, vol. 15, no. 1, p. 2013, Mar. 2024, doi: 10.1038/s41467-024-46245-4.
- [4] A. Ofner *et al.*, “High-Throughput Step Emulsification for the Production of Functional Materials Using a Glass Microfluidic Device,” *Macromolecular Chemistry and Physics*, vol. 218, no. 2, p. 1600472, 2017, doi: 10.1002/macp.201600472.
- [5] Y. Cao *et al.*, “Permanent magnetic droplet-derived microrobots,” *Science Advances*, vol. 11, no. 28, p. eadw3172, Jul. 2025, doi: 10.1126/sciadv.adw3172.
- [6] T. Zhang, S. Jiguet, A. Bertsch, and J. Brugger, “Microfluidic synthesis of alumina particle-laden beads via capillary number tuning for varying particle concentrations,” *Microfluid Nanofluid*, vol. 30, no. 6, p. 49, Jun. 2026, doi: 10.1007/s10404-026-02905-z.