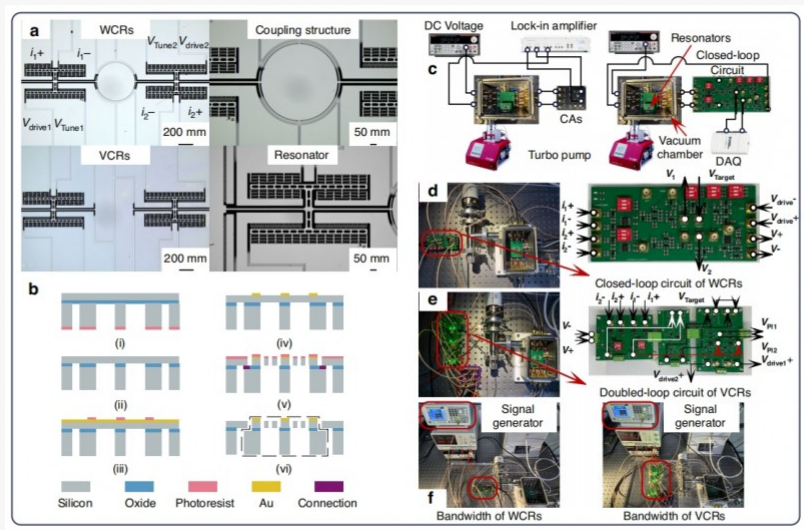
Physically decoupled, performance amplified: a new design for resonant sensors

FAYETTEVILLE, GA, UNITED STATES, June 16, 2025 /EINPresswire.com/ -- A new design paradigm in microelectromechanical systems (MEMS) is tackling longstanding trade-offs between sensitivity and bandwidth by introducing virtually coupled resonators (VCRs). Unlike conventional systems that rely on fragile mechanical links, VCRs use intentional frequency offsets to confine energy—eliminating the need for physical coupling. This approach not only simplifies device architecture but also unlocks higher amplitude ratio (AR) sensitivity and enables a dual-loop control system for faster, more stable performance. Experimental validation reveals that VCRs achieve a 2.7-fold increase in sensitivity and at least a fourfold improvement in bandwidth over traditional weakly coupled resonators (WCRs), opening new possibilities for high-precision MEMS sensing.



a Images of the coupled resonators. b Fabrication process for the coupled resonators. c Schematic of open-loop and closed-loop test. d Closed-loop test of WCRs. e Closed-loop test of VCRs. f Bandwidth test of WCRs and VCRs.

Mode-localized microelectromechanical systems (MEMS) sensors are prized for their extreme sensitivity and their natural immunity to common-mode noise, both rooted in their ability to confine energy within weakly coupled resonators. This localization effect allows minuscule physical changes to produce pronounced output signals. However, these benefits come with limitations: traditional WCRs require delicate mechanical coupling, which restricts design adaptability, complicates control schemes, and narrows bandwidth. Moreover, theoretical explanations of energy confinement in these systems remain incomplete. Due to these challenges, there is an urgent need to explore alternative architectures that preserve sensitivity while unlocking greater bandwidth and control flexibility.

A research team from Northwestern Polytechnical University has unveiled a next-generation MEMS sensor architecture using virtually coupled resonators. Published (DOI: 10.1038/s41378-

025-00897-4) in Microsystems & Nanoengineering in April 2025, the study introduces the concept of “modal dominance” to describe energy confinement through frequency-based interactions instead of mechanical links. The team also implements a novel double-closed-loop control strategy, achieving improvements in both signal stability and real-time responsiveness—marking a significant advance in MEMS sensor design.

The study reinterprets energy confinement in weakly coupled resonators (WCRs) through the lens of “modal dominance,” where mode frequencies are governed by the natural frequencies of the individual resonators. Building on this understanding, the researchers developed virtually coupled resonators (VCRs)—two physically separate resonators that achieve functional coupling through tuned frequency offsets. This virtual coupling preserves the performance benefits of WCRs while simplifying mechanical design and enhancing tunability. To address dynamic responsiveness, the team implemented a double-closed-loop feedback system, allowing both resonators to operate in synchrony and maintain precise amplitude ratios at higher speeds. Experiments demonstrated that VCRs achieve AR sensitivities of 24.4 $(N/m)^{-1}$ in open-loop mode and 33.0 $(N/m)^{-1}$ in closed-loop, far exceeding the 9.03 $(N/m)^{-1}$ achieved by comparable WCRs. Additionally, VCRs sustained stable output at signal frequencies up to 12 Hz, whereas WCRs degraded above 2.25 Hz. These results confirm that VCRs offer both superior sensitivity and bandwidth—key metrics for next-generation MEMS sensors.

“By transitioning from mechanical to frequency-based coupling, this work redefines the design space for MEMS sensors,” said Prof. Yongcun Hao, co-corresponding author of the paper. “Virtually coupled resonators paired with dual-loop control not only streamline system architecture but also enable unprecedented gains in performance. We see this as a cornerstone technology for the next wave of high-resolution, real-time sensing.”

The VCRs framework offers compelling advantages for a broad spectrum of MEMS applications, including inertial navigation, biomedical monitoring, and environmental sensing. Its minimalist structure reduces fabrication complexity, while its enhanced sensitivity and bandwidth allow faster, more precise detection of physical signals. Crucially, the absence of mechanical coupling mitigates long-term reliability concerns. Looking ahead, the researchers aim to refine resonator isolation and control electronics, with simulations suggesting potential AR bandwidths reaching tens of hertz. Such improvements could reshape what’s possible in micro-scale sensing across scientific and industrial domains.

References
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