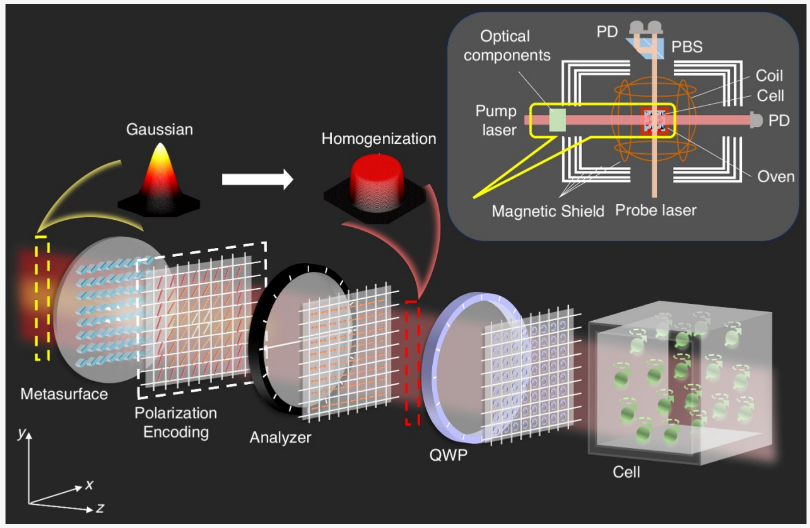
Metasurfaces smooth light to boost magnetic sensing precision



Schematic diagram of the beam homogenization method based on polarization-encoded metasurface.

GA, UNITED STATES, February 4, 2026 /EINPresswire.com/ -- High-precision magnetic sensors rely on uniform light to polarize atomic spins, yet most laser beams naturally deliver energy unevenly, limiting measurement accuracy. This study introduces a compact optical strategy that transforms a standard Gaussian laser beam into a spatially uniform pumping field by encoding intensity information into light polarization. By reshaping how light interacts with atomic ensembles, the approach reduces spin decoherence and enhances signal stability without increasing system complexity. The work demonstrates that controlling polarization, rather than reshaping intensity through bulky optics, can significantly improve magnetic measurement performance. The findings highlight a new pathway for improving the sensitivity, compactness, and robustness of next-generation quantum sensors.

Nuclear magnetic resonance–based co-magnetometers are essential tools for applications ranging from inertial navigation to geophysical exploration and biomedical sensing. Their performance critically depends on efficient optical pumping, which polarizes atomic spins through laser illumination. However, commonly used Gaussian laser beams concentrate intensity at the center while weakening toward the edges, leading to non-uniform spin polarization and accelerated decoherence. Existing beam-homogenization solutions, such as microlens arrays or spatial light modulators, often require fixed propagation distances, consume additional power, or are difficult to integrate into compact devices. Based on these challenges, it is necessary to develop an integrated, propagation-insensitive approach to achieve uniform optical pumping.

Researchers from Beihang University and Westlake University report a polarization-encoded metasurface that significantly improves optical pumping uniformity in nuclear magnetic resonance co-magnetometers. The study, published (DOI: 10.1038/s41378-025-00989-1) in Microsystems & Nanoengineering in November 2025, presents a chip-scale optical component that converts an uneven Gaussian beam into a homogenized pumping field independent of propagation distance. By combining geometric phase control with polarization filtering, the method enhances atomic spin coherence and improves magnetic sensing sensitivity, demonstrating a practical route toward more compact and precise quantum sensors.

The core innovation lies in encoding spatial intensity information into the polarization profile of light rather than reshaping the beam through conventional amplitude or phase modulation. The metasurface consists of subwavelength silicon nanoantennas whose orientations locally rotate the polarization of incoming light. When combined with an analyzer, this polarization mapping selectively transmits light to produce a flat, uniform intensity distribution across the beam profile. Importantly, the homogenized output remains stable during propagation, overcoming a key limitation of traditional beam-shaping techniques.

Experimental measurements confirmed that the metasurface significantly improved light uniformity, reducing intensity contrast across the beam cross-section. When applied to optical pumping in a nuclear magnetic resonance co-magnetometer, the homogenized beam increased both electronic and nuclear spin polarization while lowering transverse relaxation rates. These improvements translated directly into enhanced sensor performance. Under identical pumping power, the magnetic measurement sensitivity improved by approximately 23% compared with conventional Gaussian beam pumping.

The metasurface approach also offers practical advantages. Its planar, passive structure eliminates the need for bulky optics, active modulation, or additional power consumption. The device operates effectively over a relevant frequency range and is compatible with chip-level integration, making it well suited for miniaturized quantum sensing systems.

According to the researchers, optical pumping uniformity has long been an overlooked bottleneck in compact atomic sensors. By shifting the problem from intensity shaping to polarization control, the metasurface provides a fundamentally different solution that aligns with the needs of integrated quantum technologies. The team emphasizes that improving spin coherence is not only about stronger light, but about distributing light more intelligently. This work demonstrates how nanophotonic design can directly translate into measurable gains in sensor precision and stability.

The proposed metasurface-based homogenization strategy has broad implications for quantum sensing and precision measurement technologies. Beyond nuclear magnetic resonance co-magnetometers, the approach could be applied to atomic gyroscopes, chip-scale magnetometers, and other systems that rely on optical pumping. Its compact form factor and passive operation make it attractive for portable and space-constrained platforms, including navigation systems and biomedical instrumentation. More broadly, the study illustrates how metasurfaces can bridge nanophotonics and quantum engineering, offering scalable solutions that improve performance without increasing complexity. Such integration-friendly designs may play a key role in advancing practical quantum devices.

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