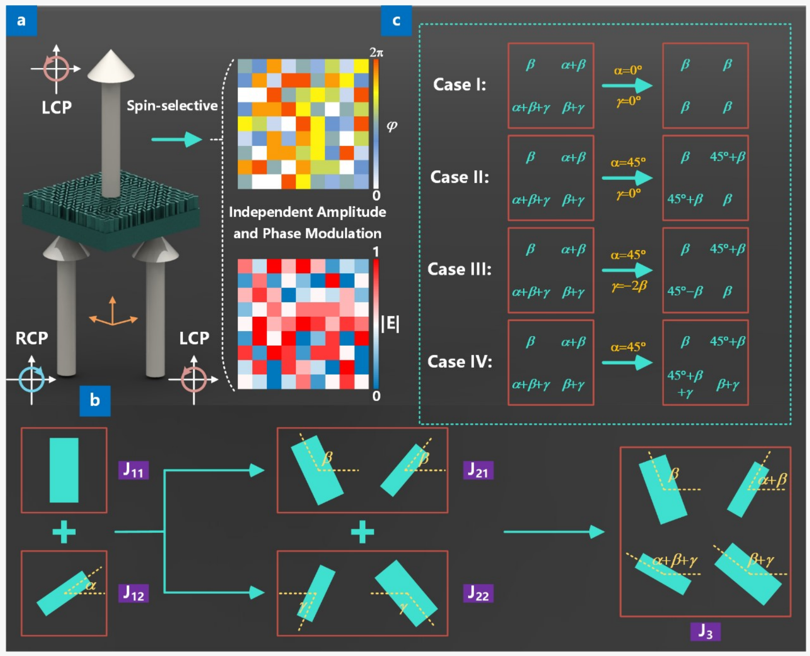
Spin-dependent amplitude & phase modulation via multifold interference via single-layer diatomic silicon metasurfaces

This research paves the way for all-silicon meta-optics that may have great potential in imaging, sensing and detection.



The design strategy for terahertz metasurfaces capable of achieving spin-selective functionality through complex-amplitude modulation is systematically categorized into four distinct parametric modulation types.

CHENGDU, SICHUAN, CHINA, May 30, 2025 /EINPresswire.com/ -- Background:
In the fields of optoelectronic technology and optical information processing, light modulation and control constitute pivotal technologies for achieving efficient optical communication, optical imaging, and sensing systems. Particularly in the terahertz (THz) frequency regime, THz technology has demonstrated broad application prospects in security screening, biomedical imaging, and communication systems due to its unique penetration capabilities and low photon energy. With advancements in micro-nano optics, metasurfaces have garnered significant attention for their ability to manipulate light properties—including phase, amplitude, polarization, and frequency—at subwavelength scales.

As an emerging optical platform, all-silicon metasurfaces enable efficient manipulation of incident terahertz waves by tailoring the dimensions, geometries, and spatial arrangements of birefringent structures. Recent research has focused on spin-dependent phenomena in metasurfaces, particularly their applications in modulating the complex amplitude of incident waves. Complex amplitude modulation, which involves simultaneous control of both amplitude and phase, offers enhanced information-processing capabilities compared to single-parameter (amplitude or phase) modulation schemes.

Furthermore, the introduction of dual-atom configurations provides an additional design degree of freedom for THz metasurfaces. Through sophisticated design, such biatomic structures can achieve intricate optical field distributions on metasurfaces, such as multiple interference effects arising from interactions between distinct atomic elements. These interference effects may amplify or suppress specific optical field characteristics, enabling high-precision light field manipulation and expanding the potential for advanced optical control strategies.

Highlights:
To advance fundamental research in terahertz photonics, a research team led by Academician Jianquan Yao from Tianjin University, in collaboration with Professor Yun Shen's group at Nanchang University, proposed a Jones matrix-based multi-geometric-phase mechanism. This mechanism enables spin-dependent complex amplitude modulation in the terahertz regime, as illustrated in Figure 1(a). By selecting two half-wave plate meta-atoms with fixed propagation phase delays ($\pi/2$) and leveraging a stepwise superposition interference mechanism, multi-dimensional terahertz optical field modulation was achieved within designated circular polarization channels. The rotation angles of the dielectric pillars along the z-axis, which define the supercell construction, are parameterized by □, □, and □, as shown in Figure 1(b).

In Strategy I, a metasurface design for terahertz holographic imaging was constructed using classical pure geometric phase modulation combined with the Gerchberg-Saxton algorithm. Strategy II elucidated the mechanism of broadband asymmetric transmission by adjusting the relative rotation angles of dielectric pillars across four quadrants, thereby enabling spin-dependent pure phase modulation in the proposed metasurface. Strategy III validated terahertz near-field imaging via a dual-atom metasurface design with pure amplitude modulation. Strategy IV further expanded this framework by introducing a generalized complex amplitude modulation scheme based on terahertz metalenses, where spin-dependent simultaneous amplitude and phase modulation was realized through multi-interference effects under distinct parameter conditions.

By integrating birefringent meta-atoms with tailored rotational configurations, the proposed design strategies offer novel solutions for applications such as chiral imaging, optical data storage, and information encryption. Experimental validation of these metasurface designs was conducted using advanced micro-nano fabrication and probe-scanning characterization platforms.

The investigation of spin-dependent complex-amplitude modulation and multiplexed interference effects in diatomic all-silicon terahertz metasurfaces is anticipated to have profound implications. This research not only advances fundamental studies in terahertz photonics, but also holds substantial potential for revolutionizing optical device architectures, enhancing photonic communication systems, and innovating high-resolution imaging modalities. Such exploration is poised to pave alternative avenues for optoelectronic technological evolution, while simultaneously establishing novel paradigms for elucidating intricate light-matter interaction mechanisms.

This research work, entitled "Spin-dependent amplitude and phase modulation with multifold interferences via single-layer diatomic all-silicon metasurfaces," was published in Volume 4 of Opto-Electronic Science (2025).

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Team introduction:
The Institute of Laser and Optoelectronics at Tianjin University (http://laser.tju.edu.cn), founded in 1988 by Academician Jianquan Yao, has evolved over three decades into a distinguished research entity. Its principal research domains encompass solid-state laser technology, fiber laser systems, terahertz (THz) science, and micro-nano optoelectronic devices. Over the past five years, the institute has undertaken over 20 national-level research initiatives including the National 863 Program, National 973 Program, National Key R&D Program, and National Natural Science Foundation projects, securing cumulative research funding exceeding 50 million CNY. The institution maintains a robust academic output with an annual average publication output of approximately 150 SCI/EI-indexed articles in prestigious journals such as Advanced Functional Materials, Nano Letters, Laser & Photonics Reviews, Photonics Research, ACS Photonics, and Journal of Lightwave Technology.

Notable technological achievements include specialized laser sources, optical-THz hybrid systems, fiber sensing architectures, and laser/THz metrology platforms, which have been strategically implemented in national priority sectors including aerospace engineering, deep-sea exploration, biomedical diagnostics, intelligent manufacturing, and nuclear technology. The research team comprises 6 full professors, 6 associate professors/senior engineers, and 1 lecturer, including:

1 Academician of the Chinese Academy of Sciences
1 National Distinguished Expert
2 Ministry of Education's New Century Excellent Talents
5 recipients of Tianjin University's "Peiyang Young Scholar" programs
2 awardees of Tianjin's Youth Science & Technology Excellence Program

Currently mentoring approximately 60 doctoral and master's candidates, the institute has produced multiple national/distinguished doctoral dissertation award nominees, National Scholarship recipients, and Huawei Scholarship winners. Sustained international collaborations are maintained with leading institutions including: University of Arizona's College of Optical Sciences (USA); Center for Research and Education in Optics and Lasers (CREOL), University of Central Florida (USA); University of Manchester (UK); Osaka University (Japan).

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