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Ambient-energy-driven space-time-coding metasurface

Ambient-energy-driven space-time-coding metasurface: all-in-one realization of energy harvesting, electromagnetic wave manipulation and information modulation

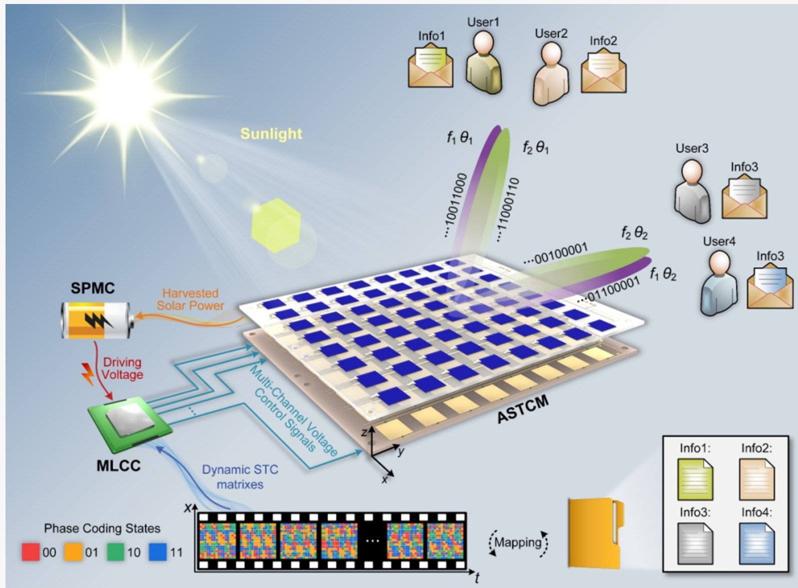

Figure 1 Schematic diagram of the ambient-energy-driven space-time-coding metasurface

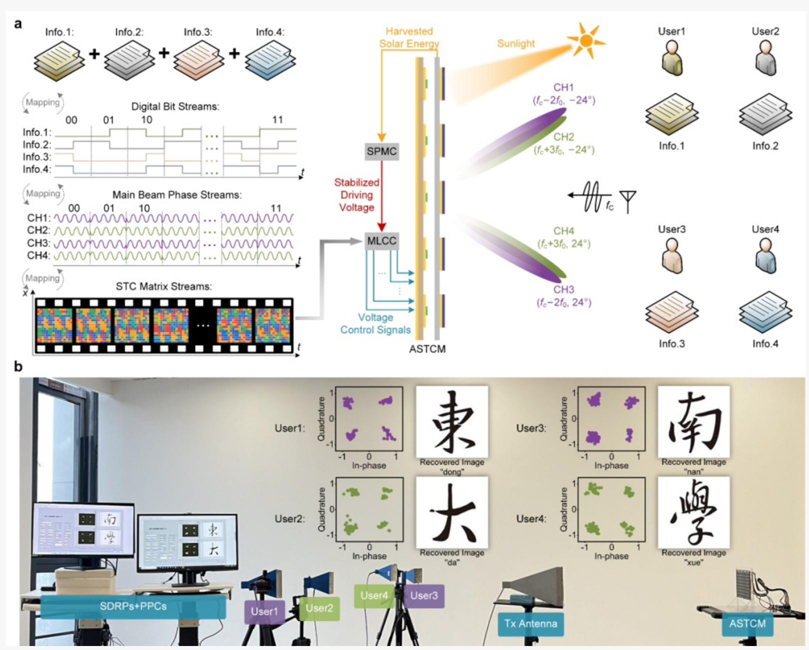

Figure 2 A high-efficiency, self-powered four-channel wireless communication system prototype based on the ASTCM

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Programmable metasurface (PM), also termed as reconfigurable intelligent surface (RIS), have emerged as a transformative enabling technology for future wireless communications due to their ability to freely and flexibly manipulate electromagnetic (EM) waves, complemented by advantages such as low cost, low complexity, and high integrability. Currently, programmable metasurfaces are developing rapidly in the field of wireless communications and can be mainly divided into two categories: (1) passive relaying surfaces that optimize the channel quality through spatial beamforming, and (2) simple-architecture wireless communication systems that directly modulate information on scattered EM waves.

In terms of information transmission, recent studies have demonstrated various multiplexing wireless communication schemes based on PMs, including frequency-division multiplexing, space-division multiplexing, space-frequency-division multiplexing, and space-frequency-polarization-division multiplexing, etc. These advancements further highlight the potential of PMs in enhancing communication capacity and enabling multi-user access. Nevertheless, the potential of PMs in this area remains to be further developed. Specifically, developing a multiplexing communication strategy that can efficiently manipulate multiple EM dimensions to expand the number of information transmission channels is crucial for further improving system communication capacity and multi-user access capabilities.

While in terms of power supply, the current situation is that most PMs are highly dependent on external power supplies. Such external, discrete power supply mode not only increases the cost, size, and complexity of PMs but also severely restricts their large-scale deployment and applicability in various application scenarios. Although several self-powered PMs with capabilities of autonomously harvesting the ambient energy (e.g., radio-frequency energy, solar energy, mechanical energy) have recently been proposed, they roughly utilize external energy harvesting devices (e.g., rectifier circuits, large-area solar panels, or triboelectric nanogenerators, etc.) to realize the self-powering function, resulting in bulky volume, low integration, and difficulties in realizing large-scale arrays.

The authors of this article propose an ambient-energy-driven space-time-coding metasurface (ASTCM) by heterogeneously integrating a solar cell chip onto each meta-atom to achieve the dynamic control of reflected EM waves and harvest ambient solar energy through sharing the same physical aperture. An innovative space-time coding method is developed, enabling the ASTCM to achieve independent multi-beamforming at multiple harmonic frequencies simultaneously. By utilizing this multi-frequency multi-beamforming capability and further modulating the phase of each beam, different frequency and space resources can be efficiently multiplexed for constructing multiple independent information transmission channels. On the other hand, a solar power management circuit (SPMC) is integrated with the ASTCM, which can effectively store and utilize solar energy harvested from the environment. Furthermore, both the ASTCM and its backend control circuits employ low-power designs, further contributing to improving the self-powering performance by reducing power consumption.

As a proof-of-concept demonstration, the research group further implemented and verified a high-efficiency, self-powered four-channel wireless communication system prototype based on the ASTCM. The system prototype constructs four independent information transmission channels by efficiently multiplexing two different harmonic frequencies and two different beam directions, with each channel employing quadrature phase shift keying (QPSK) modulation. Experimental verification showed that the system can simultaneously, independently, and in real-time transmit four different image information streams to four user terminals, with an power consumption of only 17.4 mW/bit, which is superior in energy efficiency to other metasurface-based communication system prototypes reported to date. In addition, while performing information modulation and directional transmission, the ASTCM can also harvest up to 12 mW/cm^2 of solar energy from the environment, far exceeding its own power consumption (only 0.66 mW/cm^2). A simple estimation shows that under a standard solar irradiance of 100 mW/cm^2, the ASTCM can harvest enough solar energy in approximately 1.3 hours to ensure 24-hour continuous operation.

This ASTCM technology innovatively integrates ambient energy harvesting, EM wave manipulation, and direct information modulation onto a single metasurface physical platform, opening up a brand-new path for future wireless communication to achieve high-capacity transmission, multi-user access, high energy efficiency, and green and sustainable development.
Keywords: programmable metasurfaces, space-time-coding metasurfaces, ambient energy harvesting, self-powered, multiplexing wireless communications, energy-efficient
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The research group led by Prof. Tie Jun Cui from Southeast University has conducted systematic and in-depth research in the fields of EM metamaterials and the modeling of EM scattering characteristics of complex targets and environments, achieving a series of innovative results. The research group pioneered the development of digital coding and programmable metamaterials internationally, establishing a new system of information metamaterials. Prof. Cui's research group won the second prize of the National Natural Science Award twice, in 2014 and 2018, the "Frontier Science Award" at the first International Congress of Basic Science, the IEEE Communications Society Marconi Prize. The research group led by Prof. Wei Xiang Jiang, a vital component of Prof. Tie Jun Cui's research group, has opened up a new branch of light-controlled programmable metasurfaces within the information metamaterials framework. Prof. Wei Xiang Jiang's group has also been long committed to research on high-performance lens antennas, novel EM functional devices, and light-acoustic-EM multi-physics metamaterials.
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