

New Review Explores AI-Enabled Electromagnetic Metasurfaces for Communication and Invisibility

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Programmable metasurfaces are ultrathin electromagnetic (EM) interfaces that can dynamically shape the direction, energy distribution, and spectral characteristics of waves. This review outlines how artificial intelligence (AI) is advancing these surfaces from tunable devices to adaptive systems. It summarizes their fundamental coding mechanisms, AI-assisted design and closed-loop control, and emerging applications in wireless communication and EM invisibility. Together, these developments point toward intelligent platforms capable of sensing environmental changes and responding in real time.

When mobile-phone signals are blocked by walls or other obstacles, could the surrounding propagation environment actively “lend a hand” and guide the signals toward users? When the direction of detection and the motion state of a target are continuously changing, could its EM signature be adjusted in real time so that it becomes more difficult to identify? Questions such as these once seemed highly imaginative. Today, however, they are gradually moving closer to reality through the integration of programmable metasurfaces and AI.

A metasurface is an ultrathin EM interface composed of many artificially engineered structural units that are much smaller than the wavelength of the incident wave. Each unit may be regarded as an EM “pixel” with a specific and controllable response. When these pixels are arranged in carefully designed distributions and operate cooperatively, they can reshape the

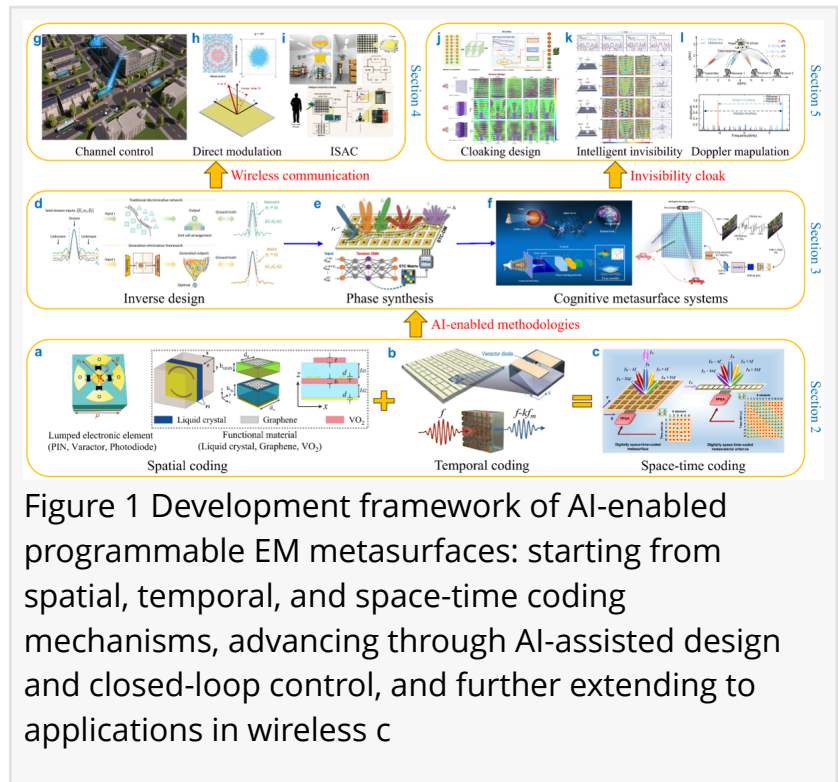


Figure 1 Development framework of AI-enabled programmable EM metasurfaces: starting from spatial, temporal, and space-time coding mechanisms, advancing through AI-assisted design and closed-loop control, and further extending to applications in wireless c

behaviour of EM waves, including their propagation direction, spatial energy distribution, polarization state, and even frequency content. In this way, a thin surface can perform functions that would otherwise require much bulkier and less flexible EM devices.

Unlike conventional components, whose operating functions are essentially fixed once fabrication is completed, programmable metasurfaces can dynamically switch or tune their working states under electronic control. This reconfigurable capability allows the same physical surface to respond to different communication tasks, environmental conditions, or detection scenarios. The incorporation of AI further extends this potential. By assisting in the search for suitable structural configurations and coding strategies, interpreting environmental information, and rapidly generating control decisions, AI enables programmable metasurfaces to move beyond simple reconfiguration toward adaptive EM operation. As a result, intelligent metasurfaces are opening new possibilities for smarter wireless communication environments and more responsive EM invisibility technologies.

Recently, a team led by Prof. Hongsheng Chen, Prof. Bin Zheng, and Researcher Jiwei Zhao at Zhejiang University contributed an invited review article entitled “AI-enabled electromagnetic metasurfaces for wireless communication and invisibility cloak” to *Opto-Electronic Technology*. Centered on programmable EM metasurfaces empowered by AI, the review provides a structured overview of recent progress in this fast-growing field. Rather than discussing individual devices in isolation, it follows a clear developmental route from physical mechanisms and intelligent methodologies to system-level applications, with a particular emphasis on wireless communication and EM invisibility.

Programmable metasurfaces are composed of large numbers of controllable subwavelength elements. Each element can be viewed as an EM “pixel” whose response may be adjusted electronically or through tunable materials. When these pixels work together under programmed control, the surface can reshape incident EM waves by changing their propagation direction, spatial energy distribution, polarization characteristics, and even spectral content. The review begins with three basic mechanisms underlying this capability. Spatial coding assigns different EM responses across the surface to redirect or reshape wavefronts. Temporal modulation changes the response of the surface over time, allowing energy at one frequency to be redistributed into new frequency components. Space-time coding combines spatial and temporal degrees of freedom, making it possible to coordinate beam direction and frequency channels within a single programmable platform. These mechanisms show how metasurfaces are moving beyond conventional beam steering toward more flexible multidimensional control of EM waves.

Building on these physical foundations, the review explains how AI is accelerating the evolution of programmable metasurfaces from tunable devices into intelligent systems. At the design stage, AI-assisted inverse design can rapidly search for meta-atom structures capable of producing desired EM responses, reducing the time and computational cost associated with repeated manual optimization. At the aperture level, data-driven methods can assist in the

synthesis of large-scale metasurface arrays and help address complex interactions among neighbouring elements. More importantly, in closed-loop systems, AI can combine information from EM measurements, visual sensing, or deformation sensing to determine updated control strategies in real time. A metasurface may therefore not only execute a predefined command, but also perceive changes in its surroundings or its own state and adapt its response accordingly.

The review further highlights two major application directions. In wireless communication, intelligent metasurfaces can actively reshape propagation environments, enhance signal coverage, track moving users, directly modulate information onto EM waves, and support integrated sensing and communication on a shared hardware platform. In EM invisibility, programmable metasurfaces can dynamically reconstruct scattering fields to achieve adaptive cloaking under changing conditions. Through temporal modulation, they may also regulate Doppler signatures detected by radar, extending EM invisibility from spatial scattering control to motion-related spectral-signature manipulation.

Taken together, these advances demonstrate that AI-enabled programmable metasurfaces are emerging as intelligent EM interfaces connecting communication, sensing, and low-observable regulation. The review also emphasizes that further progress will rely on physically reliable algorithms, efficient hardware, experimental validation, and robust operation in realistic environments.

Although AI-enabled programmable metasurfaces have demonstrated considerable potential in wireless communication and EM invisibility, their practical deployment still faces significant challenges, including low-power hardware implementation, real-time control, large-scale integration, and reliable validation in complex environments. In the future, deeper integration of programmable devices, intelligent algorithms, and sensing-feedback mechanisms is expected to drive intelligent metasurfaces beyond interfaces for EM wave manipulation. They may evolve into smart EM platforms capable of perceiving environmental changes, making adaptive decisions, and responding dynamically to diverse communication and invisibility-oriented demands, ultimately supporting more robust, efficient, and autonomous EM systems.

Keywords: programmable metasurface, space-time coding, artificial intelligence, wireless communication, invisibility cloak

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The Intelligent Electromagnetic Sensing and Control Team at Zhejiang University is led by Prof. Bin Zheng. Addressing frontiers in EM information science as well as major national needs, the team conducts research on novel artificial EM materials and metasurfaces, EM invisibility, intelligent EM control, and intelligent wireless communication. The team currently includes five faculty supervisors, eighteen doctoral students, and eleven master's students, and has established an integrated research framework that advances fundamental theory, device design, intelligent algorithms, and system-level validation in a coordinated manner. In recent years, the team has published more than 100 papers in leading journals, including

Nature Photonics, Nature Communications, and Science Advances, and has been granted more than 40 invention patents. It has also undertaken multiple national-level research projects and achieved a series of advances in intelligent metasurface-enabled invisibility, programmable EM control, and related engineering applications.

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