

Opto-Electronic Advances

CN 51-1781/TN ISSN 2096-4579 (Print) ISSN 2097-3993 (Online)

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Citation: Zhan HJ, Gu MN, Tian Y, et al. Review for wireless communication technology based on digital encoding metasurfaces. *Opto-Electron Adv* 8, 240315(2025).

<https://doi.org/10.29026/oea.2025.240315>

Received: 26 December 2024; Accepted: 3 March 2025; Published online: 8 July 2025

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Review for wireless communication technology based on digital encoding metasurfaces

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Metasurfaces offer exceptional capabilities for controlling electromagnetic waves, enabling the realization of unique electromagnetic properties. As communication technology continues to evolve, metasurfaces present promising applications in wireless communications. This paper reviews the latest advancements in metasurface research within the communication sector, explores metasurface-based wireless relay technologies, and summarizes various wireless communication methods employing different types of metasurfaces across diverse modulation schemes. This paper provides a detailed discussion on the design of wireless communication systems based on coding metasurfaces to simplify transmitter architecture, as well as the development of intelligent coding metasurfaces in the communication field. It also elaborates on the application of vector vortex light fields in metasurface communication. Finally, it offers a forward-looking perspective on wireless communication systems that incorporate coded metasurfaces. This review aims to furnish researchers with a thorough understanding of the current state and future directions of coded metasurface applications in communications.

Keywords: coding metasurface; RIS; wireless communications; signal modulation; transmitter; vortex light

Zhan HJ, Gu MN, Tian Y et al. Review for wireless communication technology based on digital encoding metasurfaces. *Opto-Electron Adv* 8, 240315 (2025).

Introduction

Metasurfaces are artificial structures formed by arranging sub-wavelength scale units of a specific geometry in a periodic or non-periodic arrangement¹, which are capable of realizing unique electromagnetic (EM) properties that are difficult to obtain in nature^{2–6}. Over the past decade, metasurfaces described by effective medium theory have been widely used to manipulate electromagnet-

ic waves, leading to numerous physical applications such as negative refraction^{7–10}, lenses^{11,12}, and high-resolution imaging^{13,14}. These applications have opened up new fields of research in metasurfaces, sparking great interest in their potential uses within the scientific community. As a two-dimensional special form of metamaterials, metasurfaces have the advantages of simple design, low cost, low profile, and low loss, and have been widely

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Received: 26 December 2024; Accepted: 3 March 2025; Published online: 8 July 2025



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applied in fields such as holography^{15–32}, microwaves^{33–37}, terahertz^{38–48}, optics^{49,50}, and electromagnetic wave control^{51–66}.

Traditional electromagnetic materials regulate electromagnetic waves solely based on their inherent permittivity and permeability. In contrast, metasurfaces enable flexible control over wavefront, polarization, amplitude, and phase by precisely designing the unit cell structure, including its dimensions and geometry. This unique capability gives metasurfaces distinct advantages in electromagnetic wave manipulation. For example, metasurfaces can introduce local phase gradients to achieve nontraditional optical effects such as anomalous reflection⁶⁷ and beam deflection^{68–70}. Moreover, by adjusting the unit cell geometry and material composition, metasurfaces can efficiently manipulate electromagnetic waves across different frequency bands, significantly expanding the potential for information transmission.

In 2011, the concept of generalized Snell's law based on metasurfaces was introduced, allowing for flexible control of electromagnetic wavefronts and offering new perspectives for metasurface design and application⁵. As metasurfaces began to be applied in electromagnetic wave technologies, various active components, such as PIN diodes, were integrated into their design. These components enable the control of electromagnetic waves through external excitations^{71–74}. In 2014, Academician Cui's team introduced the concept of digitally coded metasurfaces⁷⁵. They innovatively employed discrete digital states to represent the electromagnetic properties of metasurfaces, enabling digital control of electromagnetic information and opening new avenues for wireless communication development. By integrating digitally coded metasurfaces with programmable devices, such as field-programmable gate arrays (FPGA), these metasurfaces can now dynamically alter their functions in real-time⁷⁶. This integration overcomes the traditional limitation of metasurfaces, which typically have a fixed function post-manufacturing, by facilitating real-time, dynamic control of electromagnetic waves through reconfigurable coding metasurfaces^{77–80}.

Encoding metasurfaces provide a novel approach to signal control in wireless communication systems. By tuning the structural parameters of metasurface unit cells, they can flexibly modulate electromagnetic wave propagation paths, beam patterns, and modulation schemes. Compared to conventional wireless communi-

cation systems that rely on antenna arrays and phased array technology for beamforming and channel optimization, encoding metasurfaces achieve similar functionalities with a more compact footprint by directly manipulating electromagnetic waves. On one hand, metasurfaces optimize wireless channels through wave reflection and refraction, enhancing signal coverage and transmission efficiency. On the other hand, digitally encoded metasurfaces can dynamically reconfigure beamforming and real-time modulation by rapidly switching unit cell states, enabling adaptability to complex electromagnetic environments. In multi-user multiple-input multiple-output (MIMO) systems, encoding metasurfaces can dynamically adjust beam directions based on user positions, significantly improving system capacity and signal quality. Compared to traditional reconfigurable intelligent surfaces (RIS), encoding metasurfaces offer higher degrees of freedom, lower power consumption, and enhanced programmability, presenting a promising solution for future 6G communication technologies.

This paper reviews the latest research advancements in communications based on coding metasurfaces. First, the basic concepts of metasurfaces and their importance in wireless communications are introduced. Next, the wireless relay technology based on digital metasurfaces is discussed in detail, covering key technologies such as channel estimation, channel modeling, and beamforming. Then, the information modulation methods based on coding metasurfaces are analyzed, exploring the working principles and applications of digital coding metasurfaces, time-domain coding metasurfaces, and space-time coding metasurfaces. Subsequently, the transmitter architecture and novel wireless communication systems based on coding metasurfaces are explained, including the design of transmitters such as frequency shift keying (FSK), phase shift keying (PSK), and quadrature amplitude modulation (QAM), as well as direct radiative coding metasurface wireless communication and multi-channel direct communication systems. We also provide a detailed analysis of the superior performance of intelligent coding metasurfaces over traditional metasurfaces in controlling electromagnetic waves. Finally, we discuss the future development directions of vector vortex light field communication based on metasurfaces, and explain two methods used in communication: orbital angular momentum (OAM) and OAM multiplexing, as shown in Fig. 1.

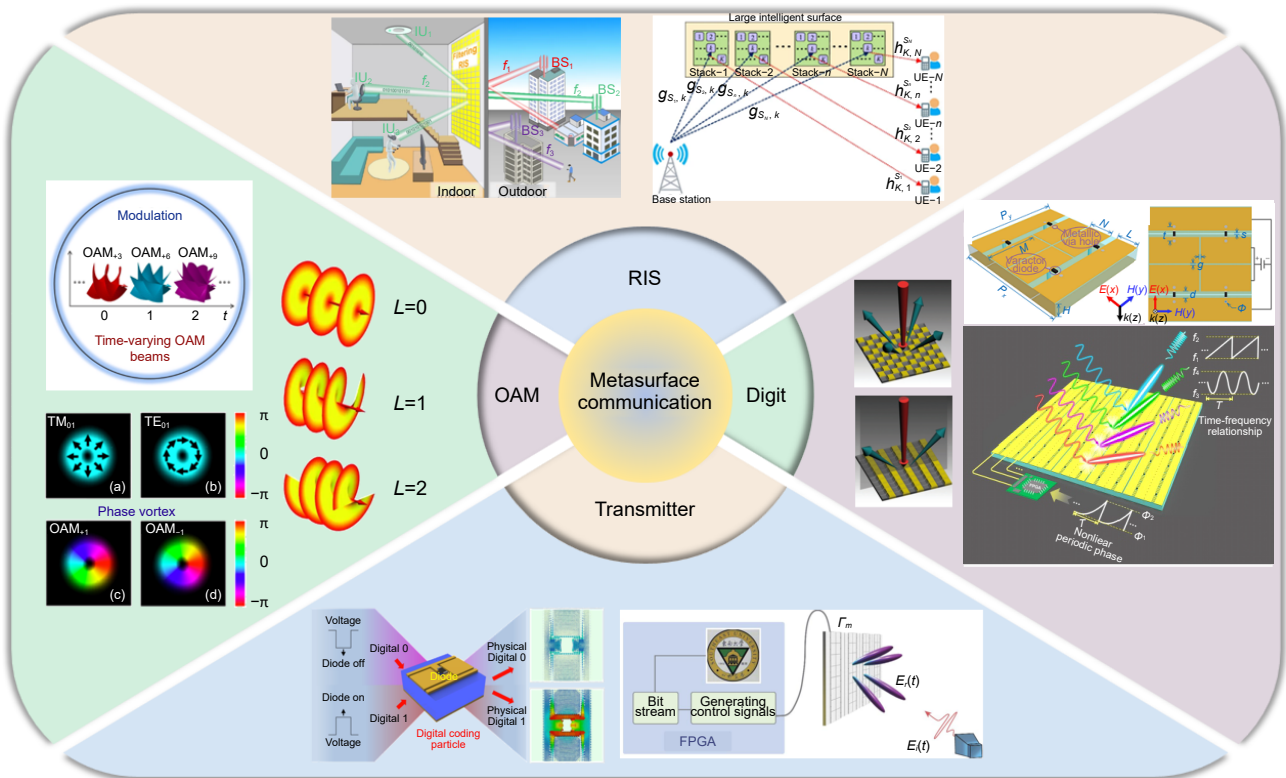


Fig. 1 | Typical applications of metasurfaces in the field of wireless communications include RIS (Reconfigurable Intelligent Surface-based wireless relay systems)^{81,82}, Digit (Digitally coded metasurface-based communication systems)^{75,83,84}, Transmitter (Novel transmitter architectures based on coded metasurfaces)^{85,86}, and OAM (Orbital Angular Momentum communication using coded metasurfaces)^{87,88}. Figure reproduced with permission from: ref.^{75,81–84}, Springer Nature; ref.⁸⁵, Oxford University Press; ref.^{86–88}, under a creative commons Attribution License.

Wireless relays based on digital metasurfaces

Fundamental principles and communication methods of metasurfaces

Metasurfaces can be categorized into passive, active, and semi-active types based on the presence of integrated active components. Passive metasurfaces consist primarily of dielectric or metallic unit structures, which regulate electromagnetic waves by modifying parameters such as material composition, size, geometry, and orientation. As illustrated in Fig. 2(a) and 2(b), metallic metasurfaces can achieve specific electromagnetic properties by altering the unit cell height and aperture size, thereby modifying the effective capacitance of each unit⁸⁹.

Figure 2(c) is a schematic diagram of the antenna. By introducing localized geometric perturbations to a perforated perfect electric conductor (PEC) parallel-plate waveguide, the amplitude A , phase Φ , and polarization states ψ and χ of the aperture field can be independently controlled at each point. Figure 2(d) illustrates the rotational characteristics of the unit structure, where the ro-

tation of the slot controls the linear polarization state of the radiation, thereby modifying the radiation characteristics⁹⁰. Due to its structural simplicity, passive metasurfaces offer several advantages in wireless communication, including low cost, low power consumption, and ease of deployment^{91,92}. In a single-input single-output (SISO) system, the signal-to-noise ratio (SNR) of a passive metasurface communication system is proportional to the square of the number of metasurface unit cells⁹³.

Semi-active metasurfaces incorporate embedded active sensing units, which operate alongside passive reflective elements to provide additional channel estimation functionality. These sensing units are equipped with RF chains and analog-to-digital converters connected to a reconfigurable impedance matrix controller⁹⁴. Due to their specialized design, semi-active metasurfaces can function for both sensing and communication applications. Metasurface-based wireless relays are typically classified into transmissive and reflective types and are often deployed on building rooftops or interiors to amplify signals. Both transmissive and reflective metasurfaces introduce functionalities such as active beamforming,

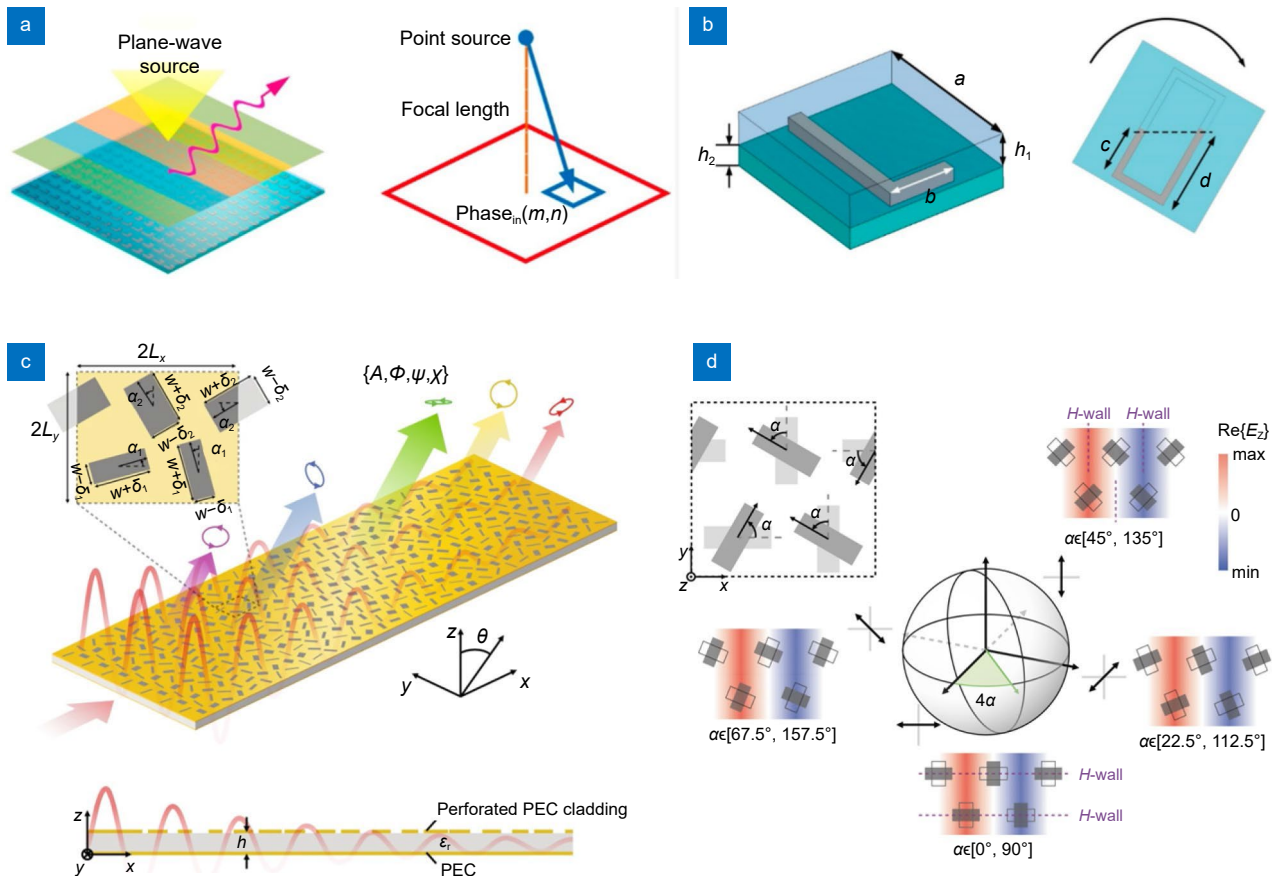


Fig. 2 | The schematic of the presented reconfigurable metasurface antenna. (a) The anomalous refraction under plane-wave incidence. (b) The incident phase calculation of the point source feed. (c) Leaky-wave metasurface antenna supporting quasi-bound states in the continuum. (d) Control of the linear polarization state of radiation through rotation of the slots. Figure reproduced with permission from: (a, b) ref.⁸⁹, Springer Nature; (c, d) ref.⁹⁰, under a creative commons Attribution License.

signal amplification, frequency conversion, channel allocation, and encoding. Figure 3(a)⁹⁵ and 3(b)⁹⁶ illustrate two typical RIS hardware architectures, each consisting of a three-layer substrate and an intelligent controller. The outermost layer is a dielectric substrate populated with regularly arranged metasurface unit cells composed of metals, dielectrics, and tunable components such as PIN diodes. As tunable elements, the switching states of PIN diodes are directly influenced by their bias voltage, thereby modulating the electromagnetic properties of the unit cells. When a PIN diode is in the "ON" state, it conducts, allowing current to flow through the diode, which alters the electromagnetic characteristics of the unit cell, such as capacitance and inductance, thereby modifying the response of the surface to incident electromagnetic waves in terms of phase and amplitude. Conversely, when the PIN diode is in the "OFF" state, it becomes non-conductive, preventing current flow and leading to a different electromagnetic response. By precisely adjust-

ing the bias voltage of these diodes, the electromagnetic properties of each unit cell can be controlled, enabling efficient manipulation of incident electromagnetic waves. The middle layer consists of a copper ground plane, which prevents signal energy leakage. The innermost layer contains the control circuitry, responsible for delivering control signals to each unit cell to modulate its electromagnetic properties.

Active metasurfaces integrate a tunable component into each unit cell, typically regulating electromagnetic waves in a reflective manner. The reflection phase of the surface is controlled by adjusting the bias voltage applied to varactor diodes. By encoding the metasurface through the application of a reflection phase gradient, the resulting phase distribution governs the angle of the reflected beam, as depicted in Fig. 3(c)⁹⁷. Additionally, a sensing circuit integrated into the bottom layer of the metasurface delivers control voltages to the varactor diodes. Based on the designed equivalent circuit,

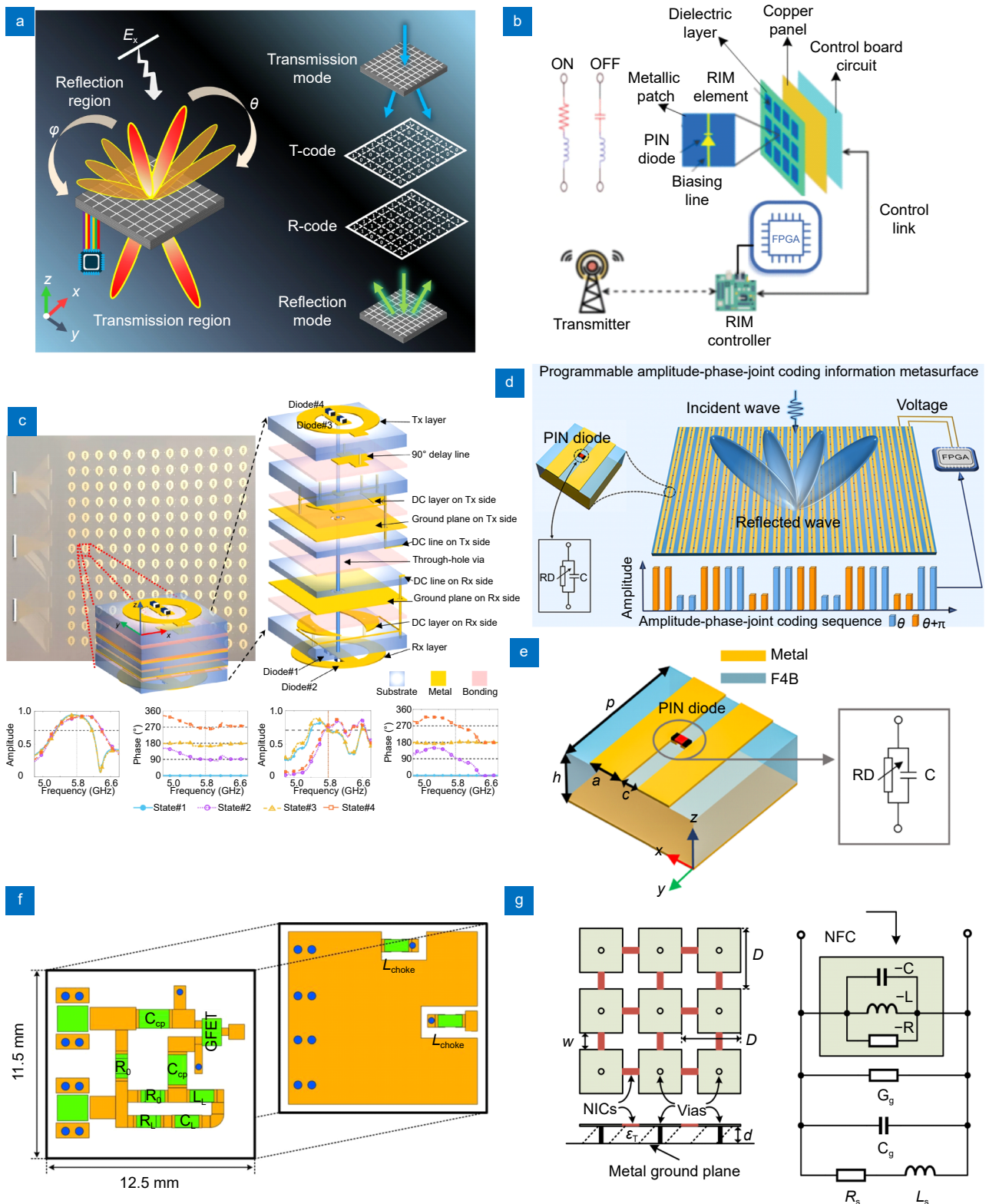


Fig. 3 | (a) Schematic of a typical reflective RIS structure. (b) Schematic of a discrete reflective RIS structure. (c) The fabricated RTM and its exploded view of the proposed unit-cell. (d, e) FPGA-controlled reflective metasurface structure and its unit cell diagram. (f, g) Bandwidth-enhanced high-impedance metasurface with non-Foster circuit loading: substrate, array, and unit cell schematic. Figure reproduced with permission from: (a) ref.⁹⁵, Springer Nature; (b) ref.⁹⁶, under a creative commons Attribution License; (c) ref.⁹⁷, Springer Nature; (d, e) ref.⁹⁸, American Chemical Society; (f, g) ref.⁹⁹, under a creative commons Attribution License.

varactor diodes can theoretically provide arbitrary voltages, enabling unit cells to generate arbitrary phase shifts⁹⁸. The active metasurface proposed by Wang et al. is shown in Fig. 3(d), where the FPGA outputs voltage to control the metasurface units. The unit structure is depicted in Fig. 3(e), where PIN diodes are embedded in the top-layer metal of the unit. The switching state is controlled by the voltage output from the FPGA.

Although metasurface unit cells incorporating tunable elements such as varactor diodes and PIN diodes allow for tunable resonance frequency and impedance, their operational bandwidth is inherently limited. To address this limitation, Fig. 3(f) and 3(g) propose metasurfaces that leverage high-impedance surfaces and non-Foster circuits to extend bandwidth⁹⁹. In these structures, the electromagnetic properties of the metasurface are dynamically tuned by adjusting the conductivity of graphene, overcoming the energy storage constraints of traditional circuits and achieving broadband response. In cascaded channels, this type of metasurface significantly reduces path loss. Therefore, while passive metasurfaces offer advantages such as low cost, active metasurfaces can effectively mitigate multipath fading and enhance

communication capacity^{100,101}.

In communication systems assisted by RIS, there are three types of channels: the direct channel (from the base station to the user), the indirect channel (from the base station to the RIS), and the reflected channel (from the RIS to the user). Figure 4 lists several typical applications of coding metasurface-based intelligent wireless environments, such as signal coverage extension, secure communication, interference suppression, large-scale device-to-device (D2D) communication, and simultaneous wireless information and power transfer (SWIPT) for IoT networks^{102,103}.

In RIS-assisted wireless communication systems, the transmission paths of signals become flexible and variable, interacting with the dynamically changing wireless environment. Electromagnetic waves reach the receiver through various means such as direct transmission, reflection, or scattering. The relative positions between the base station and the user also significantly impact the communication quality. Therefore, understanding and optimizing the channel environment is crucial for enhancing system performance.

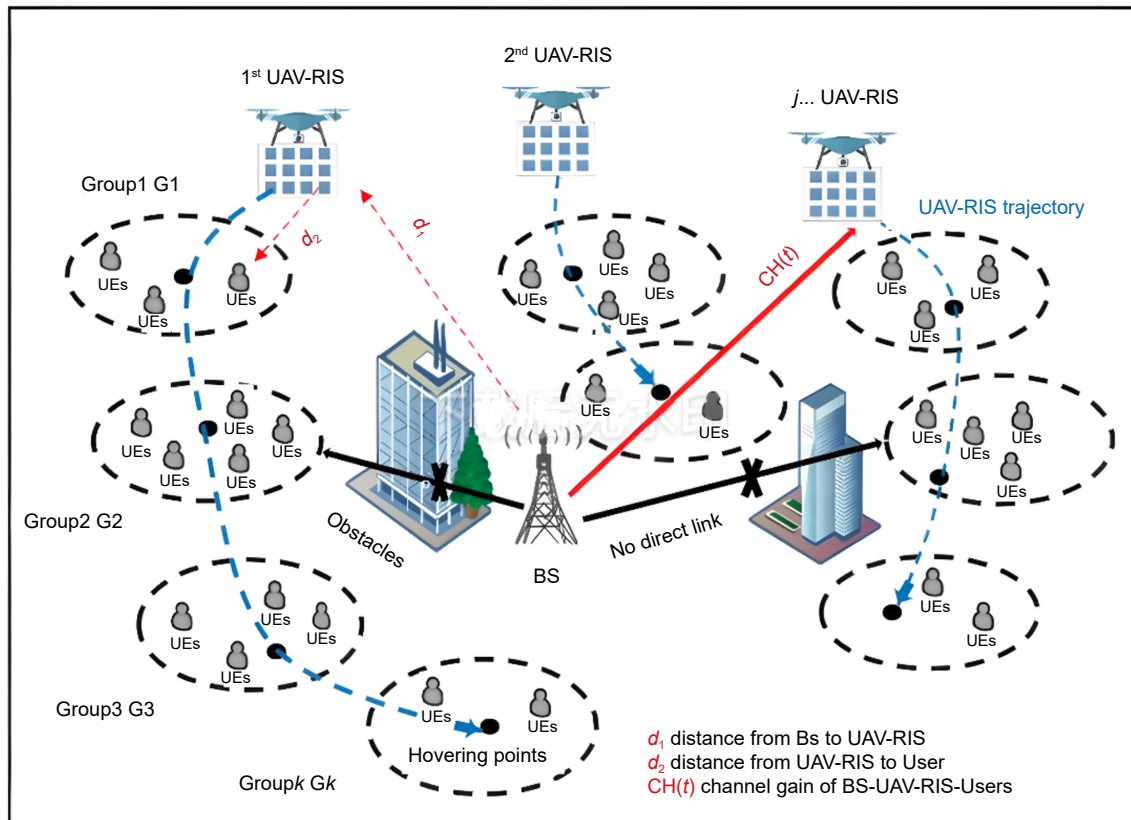


Fig. 4 | Several typical applications of coding metasurface-based intelligent wireless environments. Figure reproduced with permission from: ref.¹⁰³, Springer Nature.

Channel estimation

Channel estimation is crucial in RIS-assisted communication systems. High-precision channel estimation can enhance signal transmission efficiency and overall system performance. Existing research has proposed various channel estimation methods, including those based on compressive sensing and deep learning approaches¹⁰⁴. RIS is a planar structure composed of numerous passive reflecting units that can intelligently adjust the amplitude and phase of incident signals, thereby reshaping the propagation environment^{81,105}. This capability enhances the spectral efficiency and energy efficiency of wireless communications^{106–109}. However, the introduction of RIS makes it more challenging to accurately obtain channel information, posing challenges for channel estimation¹¹⁰. Specifically, due to the passive nature of RIS, it becomes difficult to separately estimate the channels from the base station (BS) to the RIS and from the RIS to the user (US).

The unit structure of RIS enables precise control over the electromagnetic properties of radio frequency waves, allowing reflected signals to achieve coherent superposition or cancellation at the target receiver, thus effectively reducing co-frequency interference. The effectiveness of RIS-assisted communication heavily relies on the accuracy of channel state information. In 2021, de Araujo GT et al.¹¹¹ examined structured temporal patterns involving pilots and RIS phase shifts and proposed a tensor-based channel estimation method to improve accuracy. They modeled the channel estimation problem in metasurface-assisted MIMO systems as a third-order tensor fitting problem. They introduced two channel estimation methods: a closed-form solution based on Khatri-Rao decomposition and an iterative bilinear alternating least squares (BALS) algorithm. These methods aim to separate and estimate the BS-RIS and RIS-US channels from the received signal tensor, thereby improving performance across various scenarios.

In 2020, Wang et al.¹¹² proposed a three-stage channel estimation method in the presence of noise. This method involves designing closed-form solutions for user pilots, RIS reflection coefficients, and base station linear minimum mean square error (LMMSE) channel estimators. It utilizes LMMSE to perform channel estimation under noisy conditions and evaluates its performance through channel mean square error (MSE). By exploiting the correlation of RIS reflection channels, this method reduces the number of pilot symbols and the time required for channel estimation.

In 2023, Zhang et al.¹¹³ proposed a dual-frequency reconfigurable metasurface for real-time phase control of each unit and provided its unit structure as shown in Fig. 5(a). Similarly, a RIS with active components can also manipulate signals through reconfigurable phase shifts. Moreover, an active RIS can further amplify the reflected signal, offering superior performance in terms of reflection strength compared to a passive RIS, which only reflects the incident signal without amplification, as shown in Fig. 5(b)¹¹⁴.

In 2022, Xu et al.¹¹⁵ further studied the secrecy performance of STAR-RIS assisted non-orthogonal multiple access (NOMA) systems over Rayleigh fading channels, as shown in Fig. 5(c). In 2023, Liu et al.¹¹⁶ enabled legitimate users on both sides of the STAR-RIS to actively regulate the electromagnetic propagation environment while ensuring secrecy. They simultaneously transmitted confidential information to the base station (BS) while keeping it secure from eavesdroppers near the BS, as shown in Fig. 5(d)¹¹⁶.

In the study of RIS-assisted single-input multiple-output (SIMO) communication systems, the emergence of a novel transmission protocol has further reduced the time required for channel estimation. In this protocol, each transmission frame is divided into multiple subframes, enabling simultaneous channel estimation and passive beamforming. The method leverages the reflective states of RIS to progressively estimate the channel state information (CSI) for each sub-surface across consecutive subframes. The authors proposed an adaptive transmission protocol that optimizes channel estimation and passive beamforming processes in RIS-assisted OFDM systems by carefully allocating a small number of training symbols. The protocol groups RIS units to balance the overhead of channel estimation with beamforming performance, facilitating the transmission of short data packets. It also dynamically balances transmission delay and rate by adjusting the time intervals of training symbols. Additionally, the authors introduced a binary reflection mode (0 or π) for channel estimation based on grouped RIS units. This approach not only progressively refines the estimation of CSI for each sub-surface across consecutive subframes but also differs from existing techniques by enhancing signal transmission on data subcarriers through passive beamforming on the RIS during channel training. This enhancement effectively improves data transmission rates. In order to further reduce the channel estimation time, in 2022, Ren et al.¹¹⁷

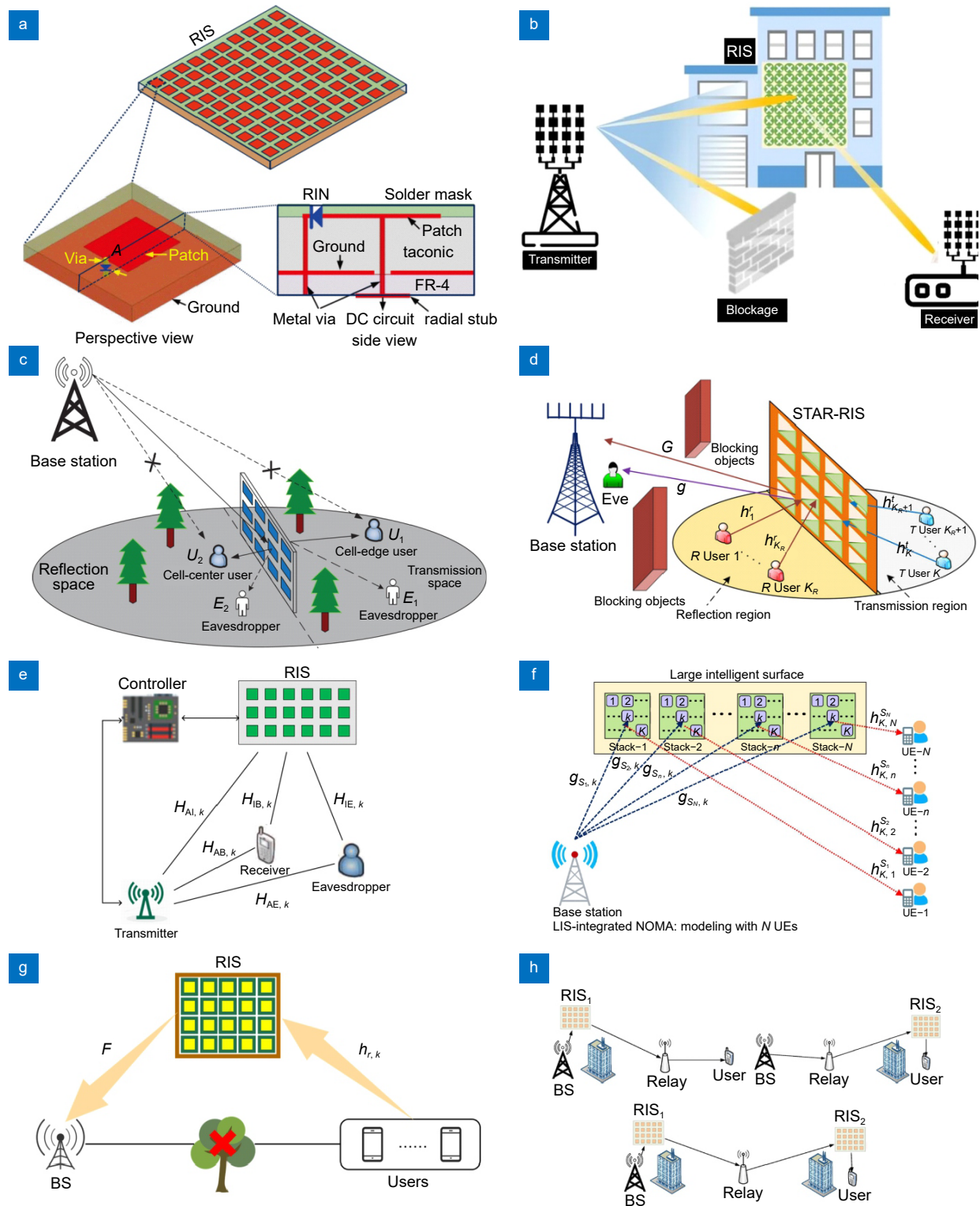


Fig. 5 | (a) Dual-frequency RIS unit structure. (b) Architecture of RIS implementation for coverage enhancement. (c) An illustration of downlink transmission of STAR-RIS-aided NOMA networks. (d) Simultaneously transmitting and reflecting reconfigurable intelligent surface (STAR-RIS) assisted millimetre wave (mmWave)-non-orthogonal multiple access (NOMA) uplink communication system. (e) RIS-enabled MIMO-OFDM secure communication scenario. (f) LIS-integrated NOMA: modeling with N UEs. (g) RIS-aided multi-user mmWave MIMO system. (h) RIS-assisted relay systems for different scenarios. Figure reproduced with permission from: (a) ref.¹¹³, under a creative commons Attribution License; (b) ref.¹¹⁴, Springer Nature; (c) ref.¹¹⁵, (d) ref.¹¹⁶, (e) ref.¹¹⁷, John Wiley and Sons; (f) ref.⁸², Springer Nature; (g) ref.¹¹⁹, under a creative commons Attribution License; (h) ref.¹²⁰, John Wiley and Sons.

discussed the more practical scenarios of the unit-modulus constraint on the reflection coefficient and the dependence between amplitude and phase shift. The communication scheme illustrated in Fig. 5(e), begins with the user transmitting pilot symbols to both the RIS and AP to assist the AP in channel state estimation. Upon receiving the pilot symbols, the AP performs initial channel estimation. The RIS controller adjusts the reflection state of the RIS, optimizing the amplitude and phase of each RIS unit to enhance signal transmission. Data signals are reflected by the RIS and subsequently captured by multiple receive antennas at the AP. By partitioning the RIS into multiple sub-surfaces and assigning a common reflection coefficient to each, the complexity and time of channel estimation are reduced by minimizing the number of independently estimated channels.

In 2021, Guan et al.⁸² proposed two new anchor-assisted channel estimation schemes. two signal anchors (A1 and A2) are inserted among the users. In proposed scheme 1, the approach first utilizes symbol uncertainty to estimate the common BS-RIS channel for all users. Subsequently, it utilizes partial CSI to uniquely resolve the desired BS-RIS-US cascaded channels. In contrast, proposed scheme 2 first estimates the BS-RIS-A1 (anchor 1) and A1-RIS-A2 (anchor 2) channels. Then, it estimates the A2-RIS-US channel to recover the cascaded BS-RIS-US channel. However, both of these schemes do not directly estimate the cascaded BS-RIS-US channels for all users. Instead, they rely on previous estimations of BS-RIS-A1/A2-RIS/BS-RIS channels or reference user's cascaded channels. Therefore, their mean square error is influenced by the accuracy of the previously estimated channels. In contrast, Bagadi, K. et al. proposed deploying a base station with a large metasurface, where the reflection coefficients of the metasurface can be controlled by adjusting passive elements, enabling simultaneous information transmission to multiple users, as depicted in Fig. 5(f),

In 2022, Guo et al.¹¹⁸ proposed a two-stage channel estimation scheme for metasurface-assisted multi-user multiple input single output (MISO) uplink cascaded channels. In the first stage, the scheme assumes no reflection from the RIS and estimates the channel in the absence of RIS, leveraging a common-link structure to reduce pilot overhead. In the second stage, assuming perfect reflection by the RIS, it estimates the channel with the presence of RIS. This approach decomposes the cascaded channel coefficients into common-link vari-

ables and user-specific variables, using the Maximum A Posteriori (MAP) criterion to formulate the optimization problem. This method avoids turning off the RIS, thereby avoiding reflection power losses, and it achieves a gain of up to 15 dB compared to other schemes. However, the optimization problem is complex and requires effective algorithmic solutions. Liu et al.¹¹⁹ proposed a linear minimum mean square error (LMMSE) channel estimation method based on orthogonal matching pursuit (OMP). In the proposed algorithm, the OMP algorithm is used to update the support set and select the column in the sensing matrix that is most correlated with the residual signal, thereby successfully reducing pilot overhead by eliminating redundancy, as shown in Fig. 5(g).

In 2025, Dong et al.¹²⁰ proposed a relay-assisted cascaded scheme, which differs from the method of Guan et al.⁸². They modeled the BS-RIS and RIS-user channels as frequency-selective fading channels. In this fading model, the amplitude and phase of the channel vary with frequency, resulting in different transmission characteristics of the signal across different frequencies. This model is more suitable for describing channel characteristics in complex multipath environments, particularly in cases involving frequency-selective fading. Figure 5(h) illustrates the relay-cascaded scenario proposed by Dong et al, where signal transmission is achieved through a cascaded RIS-Relay (or Relay-RIS) link. Two Relay are deployed near the RIS to ensure high-quality channels. Phase adjustments within the RIS are controlled by the base station and synchronized with pilot signals. Specifically, the base station can obtain partial BS-RIS CSI from Relay. This method offers advantages in terms of channel estimation error (NMSE) and data transmission BER.

In 2020, Wang et al.¹²¹ proposed a unique angle-domain cascaded channel sparse estimation technique based on traditional compressive sensing (CS). In 2021, Wei et al.¹²² developed a cascaded channel estimation scheme based on double-structured orthogonal matching pursuit (DSOMP), leveraging the sparse nature of angle-domain cascaded channels. Compared to existing methods, this approach requires fewer pilot overheads for channel estimation. However, under low signal-to-noise ratio conditions, the channel is susceptible to various non-ideal factors such as noise, leading to increased channel estimation errors. Therefore, in 2023, Liu et al.¹¹⁹ used an adaptive algorithm to mitigate external interference factors and model non-ideal channels. This method

combines the advantages of LMMSE in noise handling and utilizes the OMP algorithm to reduce channel estimation errors under low signal-to-noise ratio conditions. They proposed a LMMSE channel estimation method based on OMP, used to estimate the direct channel between the BS and US, transforming the channel estimation problem into a sparse signal recovery problem. In addition, they leveraged the dual-structured sparsity of millimeter-wave angle-domain cascaded channels and proposed a LMMSE channel estimation method based on Dual-Structured OMP (DS-OMP). This method aims to estimate the cascaded channels between BS-RIS-US. By exploiting the dual-structured sparsity of angle-domain cascaded channels, this approach achieves higher estimation accuracy with the same pilot overhead.

Channel modeling

Channel modeling is used to describe the statistical and transmission characteristics of a channel. In RIS-assisted systems, channel modeling needs to take into account multiple factors such as reflection, scattering, and fading. In recent years, a variety of channel models for complex environments have been developed to more accurately simulate signal transmission in real environments^{123,124}. Establishing a wireless communication channel can better ensure the stability of information transmission. The first thing to consider is the energy loss caused by the free space path and how to improve the stability of the channel by designing the metasurface. At the same time, it is necessary to focus on the unit coupling effect caused by imperfect hardware¹²⁵. Currently, channel modeling in coded metasurface-assisted communication systems can be divided into two categories: statistical modeling and physical modeling.

Statistical models

In RIS-assisted communication systems, the baseband equivalent channel model was initially widely used^{81,106,126}, with analyses conducted from the perspectives of cascaded channel modeling, geometric modeling, Rician fading model, and spatial domain correlation modeling¹²⁷. In 2020, Zhang et al.¹²⁸ proposed deploying a dedicated RF link in RIS to obtain the CSI of the system, but this method will increase the cost of the system.

Due to the poor penetration ability of millimeter waves and terahertz waves, RIS-assisted wireless communication systems operating in millimeter wave and terahertz scenarios result in fewer scattering paths than the

number of transmitting and receiving antennas. Therefore, these channels exhibit distinct geometric characteristics. Consequently, geometric modeling is the most commonly used modeling method in such scenarios^{129,130}. In 2022, Sun et al.¹³¹ presented a geometric channel model. They first assumed that the number of antennas at the transmitter, receiver, and RIS are N_t , N_r , and N_i , respectively. The number of paths between the UE and RIS is P , and the number of paths between the BS and RIS is Q . They then represented the overall channel from the user to the base station as follows:

$$H_{\text{overall}} = h_d + h_r^H \Theta H. \quad (1)$$

The geometric channels are expressed as:

$$h_r^H = \sqrt{\frac{N_r N_i}{P}} \sum_{p=1}^P \alpha_p a_r(\theta_r^p, \phi_r^p) a_t^H(\theta_t^p, \phi_t^p), \quad (2)$$

$$H = \sqrt{\frac{N_t N_i}{Q}} \sum_{q=1}^Q \beta_q a_r(\psi_r^q, \varphi_r^q) a_t^H(\psi_t^q, \varphi_t^q), \quad (3)$$

where, α_p , $\theta_r^p(\phi_r^p)$ and $\theta_t^p(\phi_t^p)$ are the signal gain of the p -th path between RIS and UE, the azimuth (elevation) of the angle of arrival (Ao A), and the azimuth (elevation) of the angle of departure (Ao D), respectively, β_q , $\psi_r^q(\varphi_r^q)$ and $\psi_t^q(\varphi_t^q)$ are the signal gain of the q -th path between BS and RIS, the azimuth (elevation) of arrival (Ao A), and the azimuth (elevation) of the angle of departure (Ao D), respectively, a_r and a_t are the array response vectors of the receiving end and the transmitting end, respectively.

For millimeter wave and terahertz wireless communication systems, the channel is mainly dominated by the direct path, and the channel exhibits significant sparsity, which hardly changes within the bandwidth of the studied system. In 2016, Gao et al.¹³² proposed a channel estimation scheme based on distributed compressed sensing (DCS) while studying millimeter wave massive MIMO systems, to effectively combat the frequency-selective fading (FSF) channel of millimeter waves. Compared to existing schemes, the proposed scheme can accurately estimate the FSF channel in millimeter wave massive MIMO at a lower pilot overhead, and the performance is close to the ideal situation.

Because the energy of the wave reflected by RIS is related to the magnitude of the incident wave, in RIS-assisted wireless communication systems, the way to obtain channel information is to assume that there is a line-of-sight (LOS) link between the RIS-BS and RIS-US. However, in uncontrollable scenarios with complex ob-

stacles, the multipath components brought by the environment also need to be considered. In such cases, the channel is modeled as a Rician fading model. For the m -th unit of RIS, the two segments of the channel between RIS-US and BS-RIS are represented as follows¹³³:

$$h_{r,m} = \sqrt{\frac{K_1}{1+K_1}} \bar{h}_{r,m} + \sqrt{\frac{K_1}{1+K_1}} \tilde{h}_{r,m}, \quad (4)$$

$$H_m = \sqrt{\frac{K_2}{1+K_2}} \bar{H}_m + \sqrt{\frac{K_2}{1+K_2}} \tilde{H}_m, \quad (5)$$

where: K_1 and K_2 are the Rician factors of the two channels respectively; $\bar{h}_{r,m}$ represents the channel matrix of the LOS part; $\tilde{h}_{r,m}$ represents the channel matrix of the indirect link part.

Based on the aforementioned Rician fading model, in 2020, Tao et al.¹³⁴ derived the asymptotic expressions for the channel capacity upper bound and the outage probability of the RIS-assisted network. In this context, the linear part of the channel is modeled by a Rician distribution, while the nonlinear part is modeled by a Rayleigh distribution. By analyzing the total channel gain of the RIS-assisted communication system and applying the central limit theorem (CLT), the total channel gain is approximated as a normal distribution. This approximation enables the calculation of the system's channel capacity upper bound and demonstrates that RIS can significantly enhance the system's channel capacity under optimal configuration. Furthermore, by approximating the total channel gain as a noncentral chi-squared distribution, as the number of RIS elements increases, the outage probability of the communication system can be effectively reduced, highlighting the advantage of RIS in improving system reliability.

In the scenario of RIS-assisted MIMO systems, both the RIS and user antennas are numerous, yet communication devices are becoming increasingly compact, posing greater challenges for RIS design. In 2021, Xu et al.¹³⁵ addressed spatial correlation issues between base station, RIS, and users by proposing an alternating optimization (AO) algorithm to obtain the phase shift matrix for the RIS. They also considered the impact of spatial correlation and Rician fading on the system, using large-scale system assumptions and replica method analysis to derive an approximate expression for the achievable rate of the system. In wireless communication systems, the channels between the base station and RIS, as well as between the RIS and users, are typically modeled as Rayleigh fading or Rician fading channels. However, in

practical applications, due to the dense arrangement of units within the RIS, channels exhibit spatial correlation. Therefore, in MIMO systems, it is necessary to consider spatial correlation when modeling these channels. Unlike traditional discrete antenna array models, RIS possesses unique electromagnetic characteristics and structures that require a microscopic analysis of its channel response. This entails considering the electromagnetic reflection properties at the microscopic scale within the RIS and interactions between antennas. To conduct such microscopic analysis, electromagnetic field theory and antenna array theory are typically employed for modeling. During the modeling process, it is essential to integrate the structure of the RIS surface, material properties, and electromagnetic characteristics of incident waves.

Physical model

Metasurfaces are increasingly being applied in the field of wireless communication, yet research on how wireless environments impact communication quality is still in its early stages. From a physical modeling perspective, channel characteristics are divided into free-space attenuation and electromagnetic unit response-based effects. Currently, the distance between the transmitter, receiver, and RIS is a significant factor affecting communication loss. The near-field and far-field boundaries of an RIS are defined as $L = 2D^2/\lambda$, where L , D , and λ respectively represent the distance between the transmitter and the center of the metasurface, the maximum size of the metasurface, and the wavelength of the signal. When the distance between the transmitter or receiver and the center of the RIS is less than $2D^2/\lambda$, the transmitter or receiver is considered to be in the near field of the RIS. Otherwise, it is considered to be in the far field of the RIS. Defining the distance between the transmitter and RIS as d_1 , and the distance between the RIS and receiver as d_2 , there is potential for further exploration of the relationship between free-space path loss and d_1 and d_2 in RIS-assisted wireless communication systems.

In different propagation scenarios, the relationship between spatial path loss and d_1 and d_2 varies. In 2019, Basar E et al.¹⁰⁶ studied the loss characteristics of RIS in different link scenarios by assuming the ground was covered with metasurfaces. As shown in Fig. 6(a), Fig. 6(b) illustrates the metasurface unit structure. They proposed that the optimal reflection phase makes the free-space path loss proportional to the square of the distance. In this case, the received signal strength decreases with in-

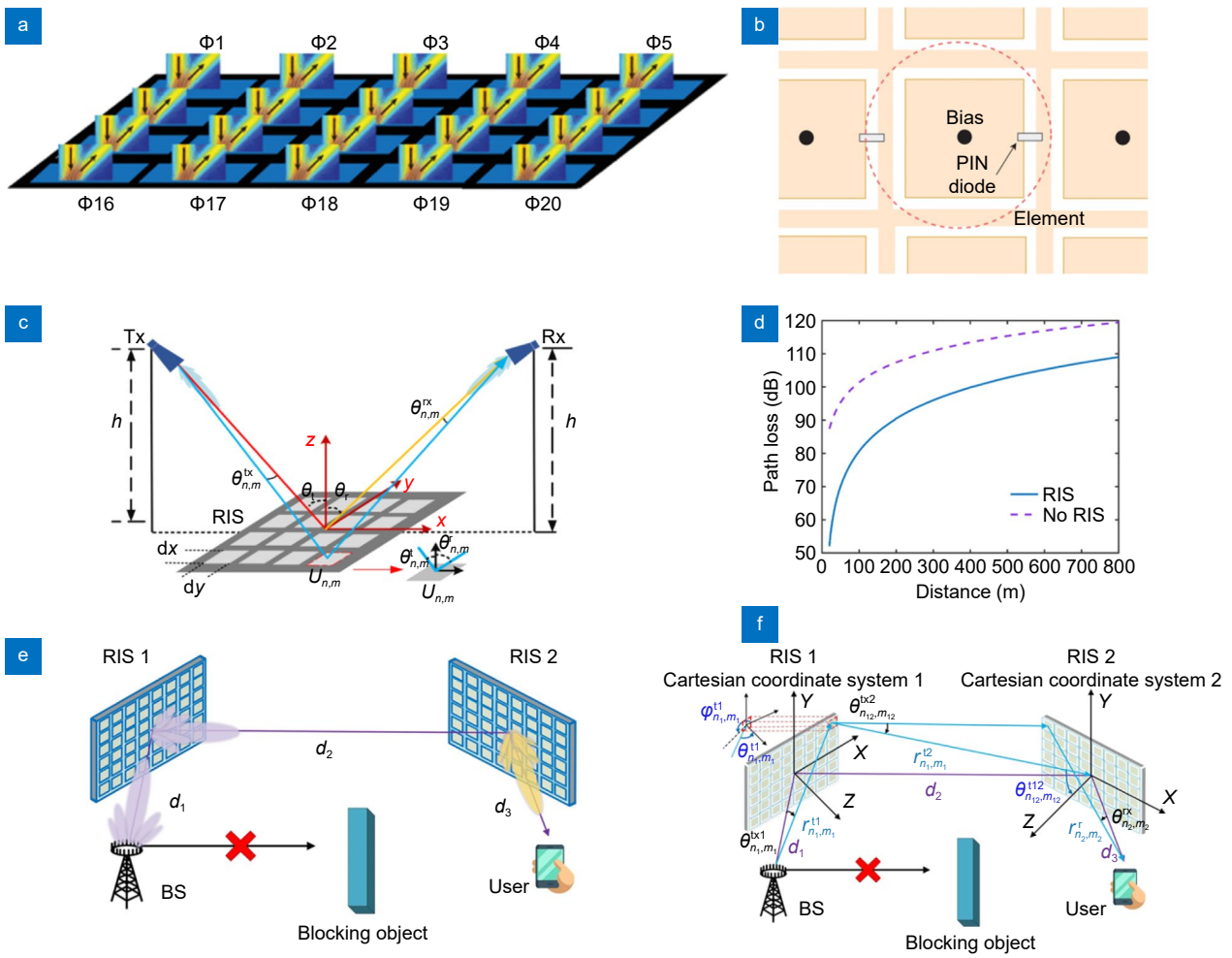


Fig. 6 | (a) Conceptual diagram of a RIS composed of 20 reconfigurable metasurfaces. (b) RIS made from active frequency-selective surfaces. (c) RIS-assisted wireless communication system. (d) Path loss variation with distance for RIS in free space. (e) Typical application scenario of double RISs-aided wireless communication systems (Only the double reflection link is included). (f) Spatial scattering channel model-based path loss modeling for the considered double RISs-aided wireless communication systems. Figure reproduced with permission from: (a, b) ref.¹⁰⁶, (c, d) ref.¹⁰⁴, under a creative commons Attribution License; (e, f) ref.¹³⁷, Springer Nature.

creasing distance, but by optimizing the reflection phase, signal attenuation can be reduced to some extent. However, this assumes the RIS is in the far field, and the proposed distance equation lacks generality as it does not account for external environmental changes.

In 2020, Özdogan O et al.¹³⁶ posited that for free-space path loss to be proportional to $(d_1 + d_2)^2$, the designed metasurface must be capable of specularly reflecting electromagnetic waves. In this scenario, the metasurface's area must approach infinity, or the metasurface must be in the near field of both the transmitter and receiver, with no obstacles between them. However, in practical situations, these requirements cannot be met. Therefore, they concluded that free-space path loss being proportional to $(d_1 + d_2)^2$ is not universally applicable. They posited that in far-field propagation scenarios, free-space

path loss is proportional to $(d_1 d_2)^2$, but this still does not address the issue of the relationship between path loss and distance in different scenarios.

In 2021, Gradoni et al.¹²⁵ introduced an end-to-end communication model tailored for RIS-assisted communication. They established this model based on electromagnetic impedance and conducted a detailed analysis within specific system configurations. This impedance-based communication model differs from traditional models by considering the coupling between transmitting, receiving antennas, and RIS elements, as well as passive scatterers within the RIS. It incorporates electromagnetic compatibility and mutual coupling awareness. This enables the model to provide more accurate and comprehensive performance predictions when analyzing and optimizing RIS-assisted communication systems.

In 2025, Yang et al.¹⁰⁴ proposed a path loss model specifically tailored for tunnel scenarios. In their proposal for non-line-of-sight scenarios, they revealed the path loss scheme in free space, highlighting the relationship between path loss, distances from the transmitter and receiver to the RIS, the size of the RIS, near-field/far-field effects of the RIS, and the radiation patterns of antenna units.

The path loss model specifically designed for tunnel

$$PL_{\text{general}} = \frac{16\pi^2}{G_t G_r (d_x d_y)^2 \left| \sum_{m=1-\frac{M}{2}}^{\frac{M}{2}} \sum_{n=1-\frac{N}{2}}^{\frac{N}{2}} \frac{\sqrt{F_{n,m}^{\text{combine}}} \Gamma_{n,m}}{r_{n,m}^t r_{n,m}^r} e^{-j2\pi \frac{(r_{n,m}^t + r_{n,m}^r)}{\lambda}} \right|^2}, \quad (6)$$

where: $F_{n,m}^{\text{combine}}$ represents the radiation pattern of the joint normalized power radiated by the transmitter, RIS, and receiver. Free-space path loss is inversely proportional to the square of the gains of the transmitter and receiver, as well as the size of the RIS units. It also depends on the number of electromagnetic units, operating frequency, distances between transmitter, receiver, and electromagnetic units, and electromagnetic gains. Additionally, path loss modeling was conducted for two classical scenarios.

First, the RIS-assisted far-field beamforming scenario, in which the free space path loss model is:

$$PL_{\text{farfield}}^{\text{beam}} = \frac{16\pi^2 (d_1 d_2)^2}{G_t G_r (M N d_x d_y)^2 F(\theta_t, \varphi_t) F(\theta_r, \varphi_r) A^2}. \quad (7)$$

Therefore, this indicates that in the far-field beamforming scenario, free-space path loss is proportional to $(d_1 d_2)^2$.

Second, RIS is used in the near-field auxiliary signal communication scenario. The free space path loss model in this case is:

$$PL_{\text{nearfield}}^{\text{broadcast}} = \frac{16\pi^2 (d_1 + d_2)^2}{G_t G_r \lambda^2 A^2}. \quad (8)$$

Therefore, this indicates that in the near-field assisted signal communication scenario, free-space path loss is proportional to $(d_1 + d_2)^2$. The relationship between free-space path loss and d_1, d_2 does not have a fixed proportionality. It depends on the radiation patterns between the transmitter, receiver, and RIS units. The model was experimentally validated by constructing a test platform. The measurement system validated the free-space path loss model in RIS-assisted wireless communication systems. By varying the propagation distances d_1 and d_2 , as well as incident and exit angles θ_t and θ_r , data

scenarios proposed by Yang et al. is illustrated in Fig. 6 (c). As observed in Fig. 6(d), the rate of path loss decreases with increasing distance, demonstrating that the use of RIS can effectively reduce path loss in wireless communication. This further validates the potential of RIS in enhancing free-space communication performance.

In the general case (where the transmitter and receiver are located at arbitrary positions), the free-space path loss model is:

testing was conducted in different frequency bands and scenarios. The validation confirmed that in the RIS-assisted far-field beamforming scenario, path loss is proportional to the square of the product of the two transmission distances. In the RIS-assisted near-field communication scenario, path loss is proportional to the square of the sum of the two distances. In 2023, Wang et al.¹³⁷ quantified the path loss of the double-reflection link in a dual-IRS-assisted wireless communication system using a spatial scattering channel model. Figure 6(e) illustrates the application scenario of dual-RIS-assisted communication, while Fig. 6(f) presents the path loss modeling based on the spatial scattering channel model with dual RIS. They further demonstrated that to maximize system performance, both RIS should have the same number of elements.

Beamforming

Although large-scale MIMO technology significantly enhances the spectral and energy efficiency of wireless communication systems, its high complexity and high hardware cost remain major limitations, especially in high-frequency wireless communication fields such as millimeter-wave^{138,139}. The emergence of intelligent metasurfaces offers a promising solution to address this issue.

Traditional metasurfaces have fixed phase-shifting capabilities after manufacturing, allowing only static regulation of incident electromagnetic waves. This limitation makes them unable to meet the dynamic requirements of mobile communications for users. However, the integration of radio frequency micro-electromechanical systems (MEMS) with RIS has made the reconfiguration of metasurfaces possible^{140,141}. This approach enables real-time control of phase shifters, allowing for flexible and

diverse regulation of the metasurfaces. Compared to continuous phase shifting, an RIS with discrete phase shifts can achieve the same squared power gain. This indicates that, regardless of the phase shifting method, RIS can deliver similar levels of signal enhancement.

In 2019, Wu et al.⁸¹ achieved beamforming and signal interference suppression by intelligently controlling the phase variations of reflecting elements. This was applied to a point-to-point MISO wireless system, where the transmitter (TX) sends signals to a single-antenna user. They proposed a centralized algorithm based on semidefinite relaxation (SDR) techniques, which jointly optimizes the active transmission beam of the AP and the passive reflection beam of the RIS. The algorithm assumes that the RIS has access to global CSI. Using this method, it is possible to maximize the received signal power at the user. They also proposed a distributed optimization algorithm, which alternates between optimizing the TX transmission beamforming and the RIS phase shifts. In this approach, one component is fixed during each optimization step, with the TX and RIS alternately adjusting the transmission beamforming and phase shifts until convergence is achieved. It is worth noting that alternating optimization itself does not imply a distributed approach. Instead, it leverages a specific structure that avoids channel feedback or signal exchange between the TX and RIS, thus reducing the complexity of channel estimation compared to centralized algorithms. Moreover, this optimization method is performed on each unit of the metasurface. Due to hardware limitations, the system requires relatively high transmission power, which results in high implementation costs. Liang et al. proposed a filtering RIS that can selectively manipulate wireless channels within a specific narrow frequency band while suppressing out-of-band signals. Figure 7(a) illustrates an example scenario to demonstrate its typical application. The filtering RIS features frequency-selective characteristics and a 2-bit phase shift capability. It allows signal transmission within a narrow bandwidth while rejecting out-of-band signals. Additionally, the phase of the transmitted signal can be digitally controlled, enabling flexible signal propagation manipulation.

Due to the significant advantages of joint optimization of active and passive beamforming in improving user signal quality and reducing complexity, this beamforming approach has been applied to various studies, such as physical layer security^{142,143}. As shown in Fig. 7(b) and Fig. 7(c), orthogonal frequency-division multiplex-

ing (OFDM)^{144,145}. As shown in Fig. 7(d) and Fig. 7(e), and SWIPT^{146,147}. However, previous studies have typically used ideal phase-shifting models that consider only the unit reflection amplitude at each reflecting element without considering the effects of phase shifts. In addition, the ideal phase shift assumption includes full reflection signals at each element, which is not achievable with current hardware. This method utilizes light detection and ranging (LiDAR) sensors to enhance user localization and beamforming in RIS-assisted networks. Integrating LiDAR sensors into the network proves highly beneficial, as they provide high-speed and precise 3D mapping even in low-light or adverse weather conditions. LiDAR data aids in user localization, enabling the determination of optimal RIS coefficients as shown in Fig. 7(f)¹⁴⁸. In 2020, Abeywickrama et al.¹⁴⁹ proposed a practical phase shift model that reflects the phase-dependent amplitude variations in the unit reflection coefficient. They used AO techniques based on iterative optimization methods to jointly optimize the active beamforming of the TX and the passive beamforming of the RIS, addressing the beamforming optimization problem under the practical phase shift model. Unlike the ideal phase shift model, the practical phase shift model requires considering the impact of phase shifts on amplitude during the joint optimization process, necessitating a balance between phase shifts and amplitude. Moreover, in the ideal phase shift model, the alternating optimization targets are the beamforming vectors and RIS reflection coefficients⁸¹. Jiang et al. proposed a joint low-complexity optimized beamforming design based on fractional programming (FP) to address the issue of increasing optimization complexity as the number of deployed base station antennas and RIS elements grows, as illustrated in Fig. 7(g). However, in the practical phase shift model, where the dependency between amplitude and phase shift must be considered, the authors proposed a low-complexity suboptimal solution. This approach optimizes the transmission beamforming vector w and the RIS reflection vector v to achieve the maximum achievable rate. It iteratively adjusts the phase shift of one reflection unit while keeping the phase shifts of the remaining units fixed, then repeats the optimization for N units until convergence is reached for all RIS units. The practical phase shift model offers higher communication efficiency and lower performance loss in real-world applications. It provides insights into studying CSI under practical RIS phase shift models and robust beamforming with imperfect CSI¹⁵⁰.

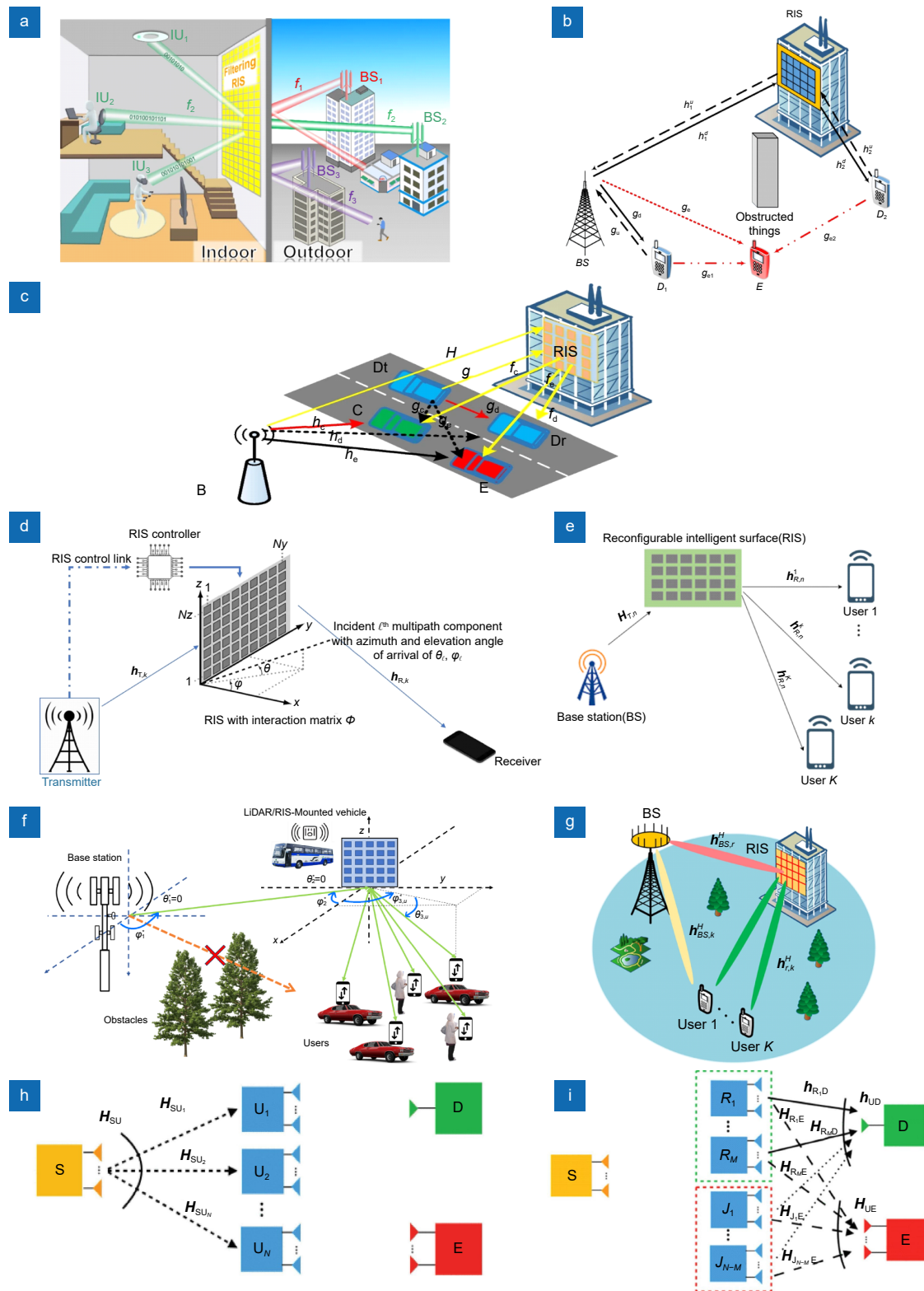


Fig. 7 | (a) RIS-based MISO wireless communication system. (b) Secure communication from the AP to the user. (c) RIS-assisted wireless secure communication. (d) RIS-enhanced wireless system. (e) RIS-enhanced OFDM communication system in the uplink. (f) System model for RIS-assisted outdoor positioning. (g) RIS-assisted multi-user communication system. (h, i) Illustration of the system model. Figure reproduced with permission from: (a) ref.⁸¹, (b) ref.¹⁴², (c) ref.¹⁴³, (d) ref.¹⁴⁴, (g) ref.¹⁴⁹, Springer Nature; (e) ref.¹⁴⁵, (f) ref.¹⁴⁶, (h-i) ref.¹⁵¹, under a creative commons Attribution License.

RIS has been widely applied to enhance spectrum and energy efficiency^{152,153}. Typically through the joint optimization of the active transmission beam of the BS and the passive reflection beam of the RIS. Currently, the perfect CSI assumed for RIS in wireless communications is idealized, representing an overly optimistic channel environment for RIS-assisted communication systems. In 2020, M. Jung et al.¹⁵⁴ studied the impact of channel errors by applying performance analysis techniques to an uplink MISO system under imperfect channel state information.

To investigate robust beamforming in RIS-assisted MISO systems with imperfect CSI, an iterative algorithm was proposed to jointly optimize the active beamforming at the BS and the passive beamforming at the RIS. This algorithm is based on approximate transformation and convex-concave procedure (CCP) to address the non-convexity issues arising from unit modulus constraints and imperfect CSI. Ultimately, they validated the relationship between the outage probability of four users assisted by RIS and the level of channel uncertainty δ , using a base station equipped with six transmit antennas. When beamforming design ignores channel errors, it typically fails to meet the target rate for at least one user, particularly at higher δ values. However, even with the worst-case robust design method, the system ensures no outages, demonstrating that the proposed iterative algorithm can effectively ensure transmission stability even without perfect CSI. In 2023, Shen et al.¹⁵¹ studied practical secure MISO wireless transmission from a source to a destination with the assistance of cooperative devices. In the first phase, space-time block coding (STBC) is used, eliminating the need for any CSI. In the second phase, the cooperative devices are divided into two groups based on whether they are used for relaying or jamming, as illustrated in Fig. 7(h) and 7(i).

In 2020, Wang et al.⁴⁵ investigated the joint design of transceivers and large metasurfaces for large-scale MIMO millimeter-wave systems. In a single-user scenario, they proposed a circular optimization algorithm to address the beamforming design problem in large-scale MIMO systems. Simulation results indicate that their proposed method achieves good performance with a smaller channel matrix condition number and has a lower complexity. This algorithm shows promising potential for widespread application in RIS-assisted millimeter-wave wireless communication systems.

Information modulation based on coded metasurfaces

Digital encoded metasurfaces

Compared to traditional metasurface technologies, digital encoded metasurfaces offer greater flexibility and programmability. They consist of numerous tiny units, each of which can adjust the reflection or transmission of electromagnetic waves according to specific digital encoding rules^{155–157}. Digital encoding metasurfaces have several key applications in wireless communication. Firstly, they allow for flexible control of electromagnetic wave reflection and transmission through different encoding sequences, enabling various beamforming and directional control techniques to enhance communication quality and coverage^{158,159}. Secondly, using programmable devices like FPGA, these metasurfaces can dynamically adjust their EM properties in real-time to adapt to rapidly changing communication needs and environments^{160,161}. Lastly, digital encoding metasurfaces can integrate multiple functionalities, such as simultaneous beamforming and interference suppression, which significantly improves the overall performance and interference resilience of the system^{162,163}.

The introduction of digital encoding metasurfaces aims to overcome the limitations of traditional metamaterial technologies, enhancing the flexibility and precision of electromagnetic wave manipulation to meet the challenges and demands of future communication and radar systems. As traditional metamaterial technologies evolve to achieve multifunctionality, their physical structures become increasingly complex, leading to greater complexity in functional analysis and design difficulties. In 2014, Cui et al.⁷⁵ introduced a groundbreaking approach by using digital encoding to characterize metamaterials, discarding the traditional method of using equivalent medium parameters. They applied different encoding sequences to the metasurface, using digital methods to flexibly control EM waves. Figure 8(a) illustrates the conceptual diagram of a 1-bit digital encoding metasurface. The digital codes "0" and "1" represent phase states of 0° and 180° , respectively. It is important to note that the 180° phase difference is relative, not absolute. By embedding active devices such as diodes into the coding elements, programmable metasurfaces were further developed to achieve real-time control of the EM field. Figure 8(b) shows the mapping relationship between the reflection phase of a 1-bit digital coding unit

and the digital codes. When the digital codes are "0" or "1", the state of the PIN diode switches between "off" and "on". Depending on the arrangement of unit cells in the metasurface, i.e., different periodic coding sequences, different types of beam scattering can be achieved. By changing the arrangement of metasurface units, such as a periodic coding sequence of "000000/111111", the incident wave on the coding metasurface can be reflected into two symmetrical directions. A coding sequence in the form of "010101/010101" can reflect the incident wave into four symmetrical beam directions, as shown in Fig. 8(c) and 8(d).

The coding elements of digital coding metasurfaces can be expanded from 1-bit to 2-bit or even multi-bit. A 2-bit coding metasurface has four coding states: "00", "01", "10", and "11", which represent reflection phases of 0° , 45° , 90° , and 145° , respectively. Figure 8(e) illustrates the implementation of the digitally controlled coding

metasurface. Four trigger switches control different coding sequences. The FPGA outputs the corresponding coding sequences, which further control the on/off states of the bias diodes, thus achieving the desired digital metasurface state.

In 2014, Giovampaola and Engheta et al.¹⁶⁶ also elaborated on the concept of digital metamaterials. However, they merely used bits and bytes of digital information to map the equivalent medium parameters and distribution characteristics of metamaterials, essentially still falling within the scope of equivalent medium theory. Digital metasurfaces have also seen considerable development in fields such as display imaging, as well as the control of surface waves and spatial propagation waves, as shown in Fig. 8(f)¹⁶⁴ and Fig. 8(g)¹⁶⁵.

Time-domain coded metasurface

Time-domain coded metasurfaces utilize the time-

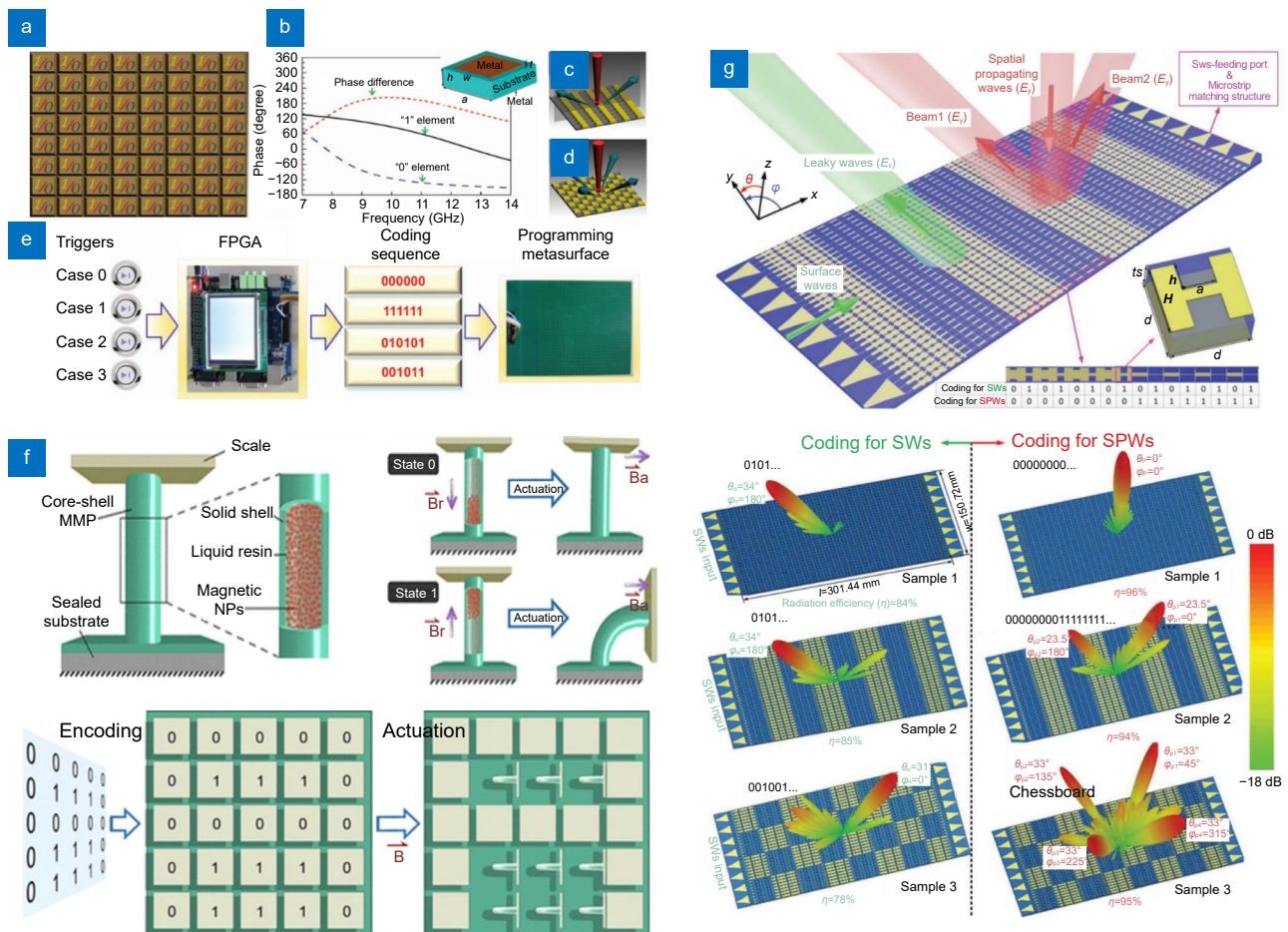


Fig. 8 | (a) 1-bit digital coding metasurface array structure. (b) Metasurface unit structure and its phase response. (c) Piano-key type coding structure of the metasurface. (d) Chessboard type coding structure of the metasurface. (e) Flowchart of FPGA-controlled coding metasurface. (f) Display imaging based on digital metasurfaces. (g) Digital metasurface beamforming control. Figure reproduced with permission from: (a–e) ref.⁷⁵, Springer Nature; (f) ref.¹⁶⁴, American chemical Society; (g) ref.¹⁶⁵, Springer Nature.

domain encoding characteristics of their microstructural units to precisely control the phase, amplitude, and propagation direction of electromagnetic waves, enabling accurate manipulation of electromagnetic signals. For 1-bit encoded metasurfaces, digital codes "0" and "1" typically correspond to phase states differing by 180° or different transmission coefficients. However, traditional spatial domain digital encoded metasurfaces generally rely on fixed spatial encoding sequences, which limits their ability to control electromagnetic beams. In contrast, time-domain encoded metasurfaces can generate arbitrary nonlinear harmonic distributions through time-domain encoding sequences, offering more flexible control capabilities¹⁶⁷. In 2018, Zhao et al.⁸⁵ proposed a novel method for controlling electromagnetic waves in the time domain using digital encoded metasurfaces, known as time-domain digital coding metasurfaces (TDCM). By modulating the reflected electromagnetic waves with a periodic function in the time domain, TDCM reflects the incident waves as a series of nonlinear harmonics, as shown in Fig. 9(a). The time-domain digital coding metasurface consists of periodic units with varactor diodes, and FPGA controls the reflection characteristics of the TDCM by loading different time sequences. By adjusting the time-domain coding states around a central frequency, several harmonic frequencies can be generated. Figure 9(b) illustrates the structure of the coding metasurface unit.

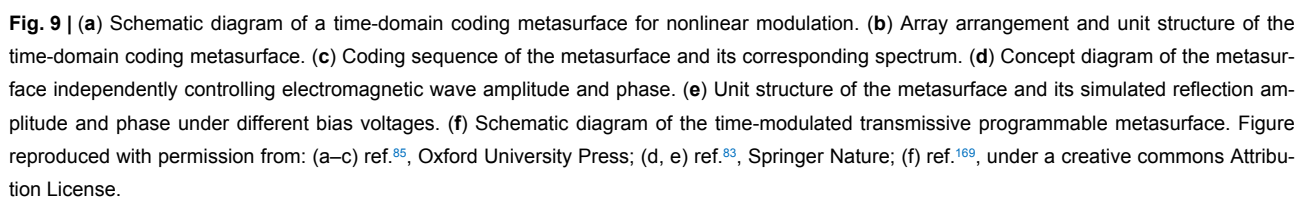
Figure 9(c) illustrates the phase modulation capability of the time-domain digital coding metasurface. For a 1-bit time coding sequence "010101", the power of the incident beam is only transmitted to the odd-order harmonics with symmetric frequency spectra, resulting in uneven energy distribution among these symmetric harmonics when transmitting electromagnetic wave signals. To eliminate all even-order harmonics except the zero-order harmonic and create an asymmetric energy distribution across the entire spectrum, a 2-bit gradient time coding sequence "00-01-10-11" was introduced. Here, the 2-bit codes "00-01-10-11" and "11-10-01-00", combined with the antisymmetric phase gradient, are used to modulate the reflectivity of the mirror-symmetric spectral distribution. The spectrum diagram shows variations in the amplitudes of different harmonics, indicating that this method has nonlinear modulation capabilities. The essential difference between nonlinear modulation and linear modulation is that linear modulation does not alter the original frequency spectrum structure of the sig-

nal, whereas nonlinear modulation changes the original frequency spectrum structure of the signal. Additionally, nonlinear modulation often occupies a wider bandwidth. By combining frequency response, polarization response, and spatial distribution, it is possible to realize a broadband passive/programmable coding metasurface capable of joint multi-dimensional control¹⁶⁸.

The main limitation of time-domain digital coding metasurfaces in controlling electromagnetic waves arises from the inherent coupling between the phases and amplitudes of different-order harmonics. In 2018, Dai et al.⁸³ proposed a novel method to achieve independent control of two characteristics by using different time-domain encoding sequences. This approach allows for the separate adjustment of phase and amplitude at different frequencies, effectively eliminating the inherent coupling between the phases and amplitudes of various harmonics. Figure 9(d) illustrates the concept of independently controlling the amplitude and phase of electromagnetic waves using a reflective digital coding metasurface. The reflection phase of the metasurface is periodically modulated in the time domain through a periodic time-domain coding sequence. The square wave varies between two pre-designed phase values V_1 and V_2 (corresponding to bias voltages V_1 and V_2). By introducing a time delay t_0 into the time-domain reflection coefficient $\Gamma(t)$, phase shifts are generated while keeping the amplitude constant at the k -th harmonic frequency, thereby breaking the inherent coupling between phase and amplitude¹⁷⁰. Figure 9(e) shows the schematic of the metasurface unit structure, where the rectangular patches are connected by four varactor diodes. By adjusting the bias voltage of these diodes, the harmonic phase varies periodically, and combined with the time-delay coding sequence, this setup allows for independent control of harmonic amplitude and phase.

Efficient and flexible control of harmonic conversion, along with breakthroughs in reciprocity constraints, is crucial for numerous applications such as modern wireless communications and radar systems. Traditional methods rely on phase shifters and amplifiers to tailor harmonics, but these devices are often expensive and complex to integrate, limiting the applicability and scalability of the systems. Recent studies have proposed a time-modulated metasurface based on modulation-induced phase shifts to break reciprocity and generate higher-order harmonics, as shown in Fig. 9(f)¹⁶⁹.

Time-domain digital coding metasurfaces can control



the reflection or transmission characteristics of each unit using specific time encoding sequences, achieving nonlinear conversion efficiency while generating multiple harmonics¹⁷¹. Additionally, they enable precise wave control at different harmonic frequencies, facilitating multiple wireless channel transmissions^{172,173}.

Spatiotemporal digital coding metasurface

Spatiotemporal digital coding metasurfaces combine spatial and temporal coding, allowing simultaneous control of electromagnetic waves in both the spatial domain and the frequency domain^{174,175}. Unlike spatiotemporal metasurfaces, spatiotemporal digital coding metasurfaces benefit from the simplified design process and efficient control provided by digital coding. They have successfully achieved various nonlinear functions, such as harmonic generation, electromagnetic parameter control, and nonlinear wavefront manipulation^{176–179}. In 2018, Zhang et al.¹⁷⁰ first introduced the concept of spatiotemporal coding metasurfaces based on digital coding metasurfaces and programmable digital coding metasurfaces, as shown in Fig. 10(a). The matrix represents the spatiotemporal coding matrix, designed by cyclically repeating a set of coding sequences within the designated time period to achieve the desired frequency-domain harmonic scattering power distribution. Each yellow unit integrates programmable devices whose electromagnetic properties can be manipulated. The external FPGA control circuit simultaneously outputs 8×8 digital coding sequences to control the characteristics of the units. Spatially, the entire metasurface acquires 64 sets of digital coding sequences, presenting a specific spatial coding distribution. Temporally, each unit is controlled by a distinct time coding sequence, with the coding states varying periodically over time. Figure 10(b) shows the unit structure, where the state of the PIN diodes corresponds to encoding states "0" or "1". This spatiotemporal coding strategy can simultaneously control the characteristics of electromagnetic wave propagation in space and the harmonic power distribution. Since the individual unit structures of the metasurface are controlled by time encoding sequences with a period of T , when electromagnetic waves pass through the spatiotemporal encoding metasurface, they generate spatial mixing effects, modulating the energy of the electromagnetic waves to various harmonic frequencies. According to the spatial encoding principle, the metasurface should exhibit the same amplitude and phase at each harmonic frequency. However,

due to the different time encoding sequences in each unit, these harmonics' frequencies and phases are modulated simultaneously. By combining this with a meticulously designed 3D time-space encoding matrix, it is possible to control the spectral distribution of electromagnetic waves while independently adjusting the electromagnetic properties of each harmonic.

In 2020, Dai et al.¹⁸⁰ used spatiotemporal coding (STC) digital metasurfaces to achieve arbitrary independent control over dual harmonics and their spatial beams. By varying the initial phase and time delay, the two harmonics can be independently controlled. The initial phase modulates the phase of the harmonics in the same manner, whereas the time delay t_0 induces different phase shifts for each harmonic without affecting their amplitudes. In 2023, Wu et al.¹⁸¹ proposed and experimentally demonstrated a synthetic moving-envelope metasurface antenna capable of simultaneously generating arbitrary harmonic orders and independently manipulating their wave properties in a software-defined manner. Figure 10(c) illustrates the control of harmonics using digital meta-atoms. Figure 10(d) shows that electromagnetic waves passing through the metasurface can undergo frequency conversion, enabling unidirectional frequency transformation.

In the field of communications, spatiotemporal coded metasurfaces for harmonic manipulation are beneficial for enhancing information transmission, as shown in Fig. 10(e)¹⁷¹. They also enable beam shaping and reflection in multi-frequency scenarios, as illustrated in Fig. 10(f)¹²⁸.

In 2023, Hu et al.¹⁸² proposed a wireless communication system with wideband characteristics based on broadband encoding metasurfaces. This system directly encodes digital information into electromagnetic waves by dynamically controlling spatial phase patterns on the metasurface aperture. The workflow of the system is shown in Fig. 11(a), with a key step being the establishment of the relationship between binary symbols and spatial-temporal encoding variations. The metasurface employs a broadband polarization-conversion design, with the basic unit illustrated in Fig. 11(b), which features a metal multilayer structure. The top metal layer consists of two intersecting rectangular patches connected by a grid structure, with PIN diodes embedded in the patches at locations where the electric field is concentrated. The second and third metal layers serve as electrodes for the bias voltage, with the second layer connected to

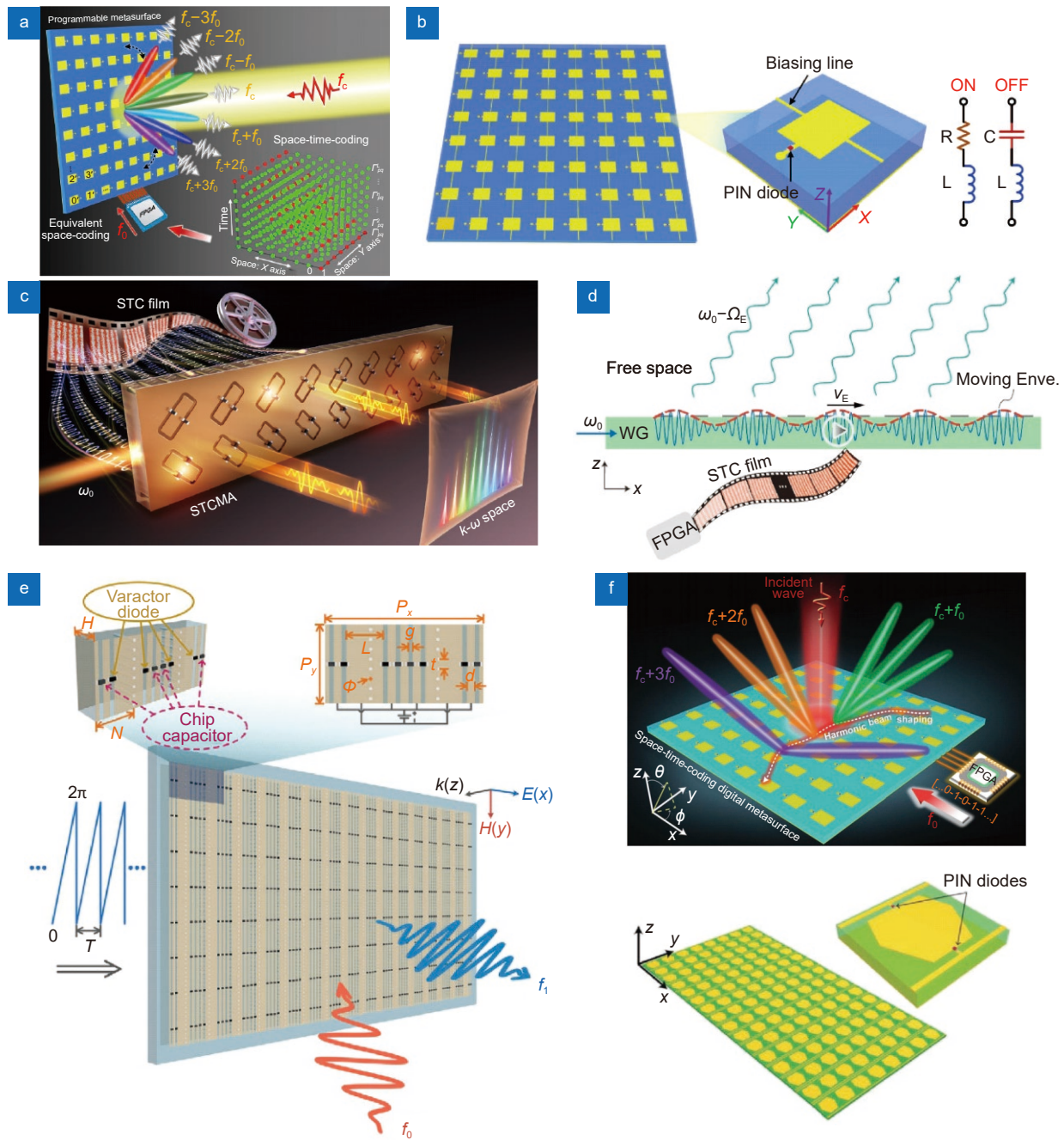


Fig. 10 | (a) T spatiotemporal coding metasurface and its spatial coding matrix. (b) Unit structure and equivalent circuit model of the spatiotemporal coding metasurface. (c) Synthetic moving-envelope metasurface antenna for arbitrary harmonic synthesis. (d) Schematic illustration of the STCMA for unidirectional frequency conversion. (e) Spatiotemporal coded metasurface for harmonic manipulation. (f) Multi-frequency beam reflection based on spatiotemporal metasurfaces. Figure reproduced with permission from: (a, b) ref.¹⁷⁰, (c, d) ref.¹⁸¹, Springer Nature; (e) ref.¹⁷¹, (f) ref.¹²⁸, John Wiley and Sons

the top metal pattern through metal vias, which act as a ground layer. Two pairs of PIN diodes oriented in orthogonal directions are always in opposite operating states, encoded as " R_0 " and " R_1 " respectively. Due to the symmetrical structure, the reflection phase difference between the two encoding states is consistently 180° , with

each meta-atom achieving 180° cross-polarization reflection by adjusting the PIN diodes.

In 2023, Hu et al.¹⁷⁷ proposed a tunable time-varying anisotropic metasurface to address the challenge of dynamically generating multiple beams with different polarizations using spatiotemporal encoding metasurfaces.

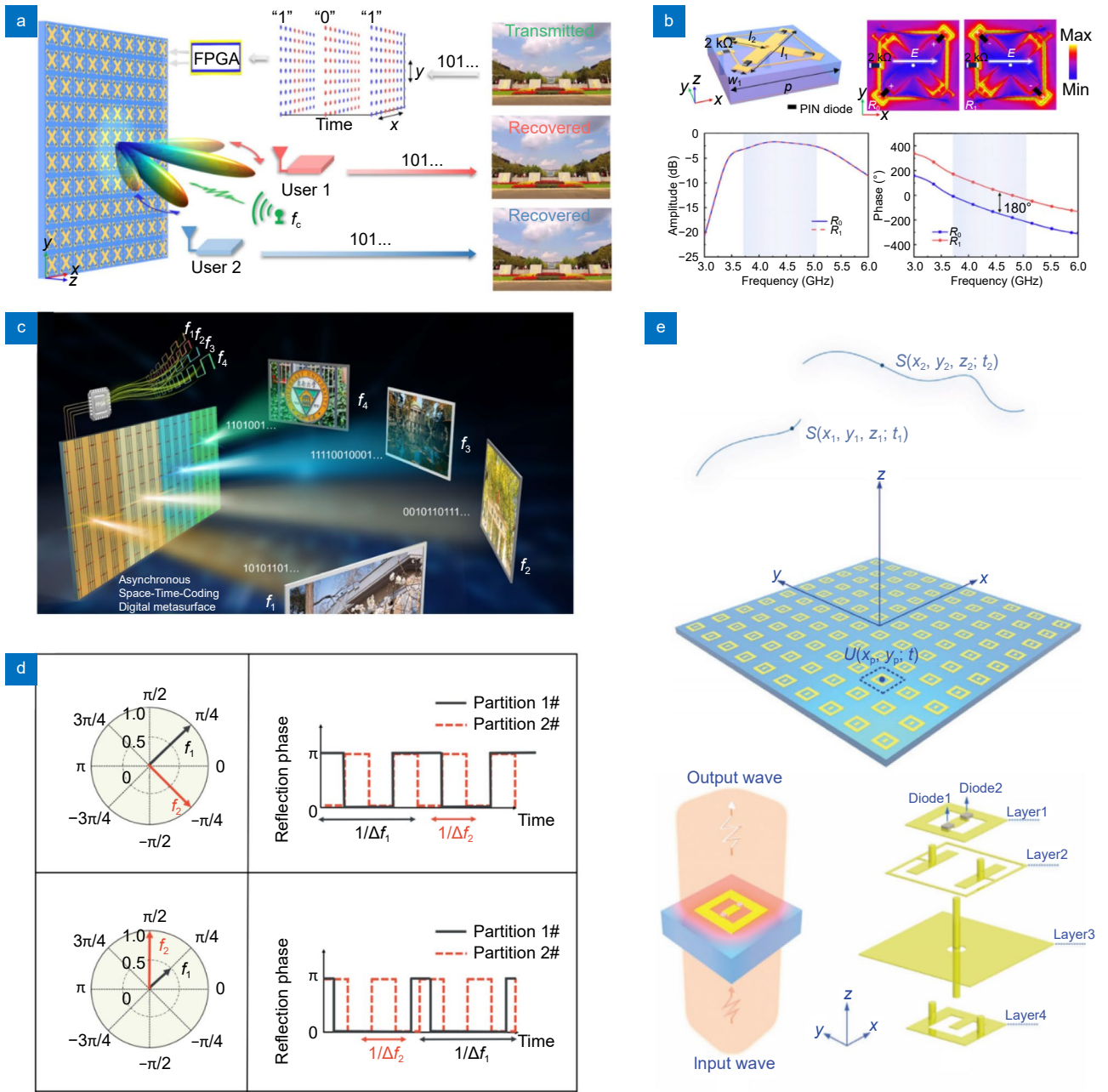


Fig. 11 | (a) Conceptual illustration of a broadband wireless communication system with beam-steering capability based on space-time-varying metasurfaces. (b) Unit structure and its simulated cross-polarization performance. (c) Schematic diagram of multi-frequency wave manipulation based on asynchronous space-time coded digital metasurfaces. Different-colored metasurface regions are responsible for wave manipulation at different carrier frequencies (f_1, f_2, f_3, f_4). (d) Phase diagrams for frequency components f_1 (black arrow line) and f_2 (red arrow line) with normalized complex amplitudes. (e) Transmission-type metasurfaces enabling spatial modulation of electromagnetic waves. Figure reproduced with permission from: (a, b) ref.¹⁸², under a creative commons Attribution License; (c, d) ref.¹⁸³, Springer Nature; (e) ref.¹⁸⁴, John Wiley and Sons.

The process involves first calculating the required polarization states for single beams, then determining the overall amplitude and phase distributions for multiple beams and polarizations. Finally, theoretical calculations are optimized to provide the desired amplitude and phase distributions. Through these steps, simultaneous generation of multiple beams and polarizations in the

microwave band was achieved, with dynamic control over their energy distribution. This tunable time-varying anisotropic metasurface exhibits powerful electromagnetic wave control capabilities, enabling efficient information transmission and multitasking through the dynamic generation of multiple beams with different polarization states.

To handle the complexity of decomposing time-domain coding sequences into sub-sequences for multi-frequency operations, in 2023, Wang et al.¹⁸³ introduced an asynchronous spatiotemporal coding metasurface (ASTCM). This method reduces the number of harmonics controlled by phase quantization, thus enhancing the metasurface's nonlinear manipulation capabilities. As illustrated in Fig. 11(c), the ASTCM uses multiple zones to generate and control nonlinear harmonics for real-time information transmission. Figure 11(d) shows the relationship between the complex amplitudes at two frequencies and the time-varying reflection coefficients of different partitions. By independently designing the reflection functions, the amplitudes and phases of the frequency components can be synthesized without mutual coupling. Adjusting the pulse delay and duty cycle of the square wave reflection waveform simplifies dual-frequency control, thereby improving the efficiency of beam manipulation.

The examples above are all based on reflective metasurfaces, but transmissive metasurfaces can still achieve spatial control of electromagnetic waves, as shown in Fig. 11(e)¹⁸⁴.

Transmitter architecture based on coded metasurfaces and novel wireless communication systems

Information metasurfaces possess powerful electromagnetic wave manipulation capabilities, enabling the construction of simplified transmitter architectures and innovative wireless communication systems. These new systems replace traditional RF components with information metasurfaces, offering advantages such as high efficiency, low cost, low power consumption, and ease of assembly. Traditional communication systems require digital-to-analog conversion, modulation, carrier loading, amplification, and microwave RF links, while transmitter architectures based on information metasurfaces can significantly simplify these steps. Composed of numerous tiny units, each unit can adjust the reflection or transmission of electromagnetic waves through specific digital coding rules. By precisely controlling electromagnetic waves, information metasurfaces achieve efficient information modulation and transmission. These new wireless communication systems can adapt to rapidly changing communication needs and environments, providing higher communication quality and coverage. The development of information metasurface technology will

drive wireless communication systems towards greater efficiency and intelligence.

FSK transmitter

In 2018, Zhao et al.⁸⁵ proposed a binary frequency shift keying (BFSK) (1-bit) transmitter system based on coded metasurfaces using phase control methods. The coding sequences ("00-01-10-11" and "11-10-01-00") effectively shift energy from the central frequency to the -1st and +1st order harmonics. These spectral lines can serve as the two discrete frequencies required by conventional BFSK communication systems. By using an FPGA to control different periodic time sequences, the digital units can generate multiple harmonics. Manipulating the time-domain coding states around the central frequency allows the generation of multiple harmonics.

The BFSK system schematic is shown in Fig. 12(a). The time-domain digital coded metasurface replaces the traditional heterodyne architecture's analog-to-digital converter (ADC) and RF network. The transmission process involves three steps: first, the FPGA generates a bit-stream of the transmitted information. Next, the bit-stream is mapped to the metasurface with the corresponding coding sequence and further extended periodically to produce a pair of discrete frequencies used in BFSK. Finally, the electromagnetic wave containing the digital information is transmitted. Figure 12(b) shows the experimental prototype setup, with a distance of 6.5 meters between the metasurface and the receiver. Figure 12(c) and 12(d) demonstrate the successful recovery of image information mapped to the metasurface at the receiving end, with the recovered image quality identical to the original. Figure 12(e) displays the spectrum received when the system transmits the binary digit "0". The power of the -1st order harmonic (-312.5 kHz) is about 20 dB higher than that of the +1st order harmonic (+312.5 kHz), allowing the receiver to easily identify the transmitted digital signal as "0". The system achieves a real-time image transmission rate of 78.125 kbps. Figure 12(f) shows the BER of the wireless communication link under different communication distances, angles, and feed antenna transmission powers, providing a quantitative evaluation of the system's performance. The results indicate that shorter distances, smaller angles, and higher transmission powers result in lower BER, which is similar to the outcomes observed in traditional communication systems.

The method that combines spatiotemporal coded

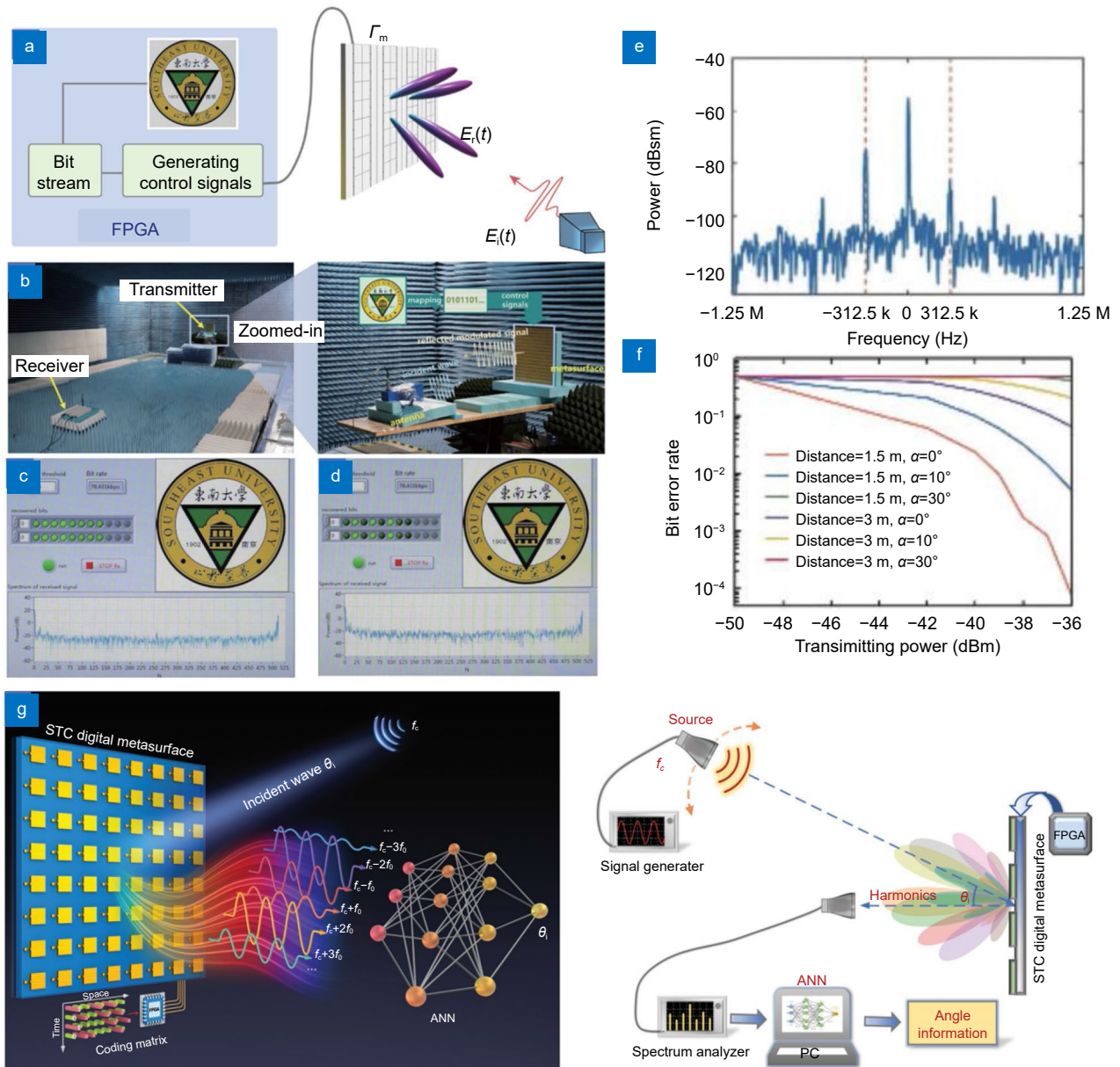


Fig. 12 | (a) BFSK wireless communication system based on a time-domain encoded metasurface. (b) Experimental setup for the BFSK wireless communication system. (c, d) Experimental results of the BFSK wireless communication system at reception angles $\alpha = 0^\circ$ and 30° . (e) Spectrum of real-time signals received by the receiver. (f) Relationship between BER of information transmission and source antenna transmission power at different communication distances and angles. (g) The combination of artificial neural networks and metasurfaces for communication applications. Figure reproduced with permission from: (a–f) ref.⁸⁵, Oxford University Press; (g) ref.¹⁸⁵, John Wiley and Sons.

metasurfaces with artificial neural networks can also simplify the transmitter architecture, as shown in Fig. 10(g)¹⁸⁵.

PSK transmitter

PSK modulation is a technique that transmits digital data by changing the phase of the carrier wave. Quadrature phase shift keying (QPSK) is a common form of PSK. In a coded metasurface QPSK transmitter, phase modula-

tion is achieved by varying the time-varying reflection coefficients of the metasurface under different bias voltages, establishing a mapping relationship between QPSK symbols and reflection coefficients. QPSK modulation includes four phase states (0° , 90° , 180° , and 270°), which correspond to combinations of two-bit data. By adding PIN diodes to the metasurface and controlling the bias voltage, the reflection coefficients are altered to achieve phase modulation. This method simplifies the system

architecture and enhances the performance and adaptability of the communication system.

In 2019, Dai et al.¹⁸⁶ proposed a coded metasurface-based QPSK transmitter. This system establishes a mapping relationship between QPSK symbols and reflection coefficients:

$$\Gamma_0 = Ae^{j(-225^\circ)} \iff '00', \quad (9)$$

$$\Gamma_1 = Ae^{j(-135^\circ)} \iff '01', \quad (10)$$

$$\Gamma_2 = Ae^{j(-45^\circ)} \iff '11', \quad (11)$$

$$\Gamma_3 = Ae^{j(45^\circ)} \iff '10'. \quad (12)$$

Specifically, each reflection coefficient can be represented by a 2-bit binary code, achieved through a time-domain 2-bit encoding metasurface. In practical operation, the electrical properties of the PIN diodes are adjusted by applying an external bias voltage, thereby tuning the reflection coefficients of the metasurface. If the source signal is "00111001", the reflection coefficients should change in the order of " $\Gamma_0\Gamma_2\Gamma_3\Gamma_1$ " under monochromatic wave illumination to accomplish the modulation process. This requires four periods T to complete the entire information transmission. This method eliminates the need for a mixer, reducing hardware costs and simplifying the system implementation.

Figure 13(a) and 13(b) show the transmitter architecture based on time-domain coded metasurfaces. The transmitter uses an FPGA to adjust the bias voltage of the varactor diodes in the coded metasurface units, thereby controlling the reflection phase of the metasurface. This allows for phase-level signal control, with digital information transmitted to the receiver through a horn antenna. Figure 13(c) illustrates the relationship between reflection coefficients and bias voltage. Under 4 GHz carrier excitation, the amplitude fluctuation of the reflection coefficient is 0.44, with a phase range of 255° . Figure 13(d) displays the QPSK binary constellation diagram, with colored scatter points representing selected constellation points for binary digits "00", "01", "11", and "10". The bias voltages for these points are 0, 4.2, 7, and 18 V, respectively. Experimental results show that this method simplifies the system architecture compared to traditional transmitters, eliminating the need for mixers and other microwave components. In practical scenarios, the QPSK system demonstrated real-time video transmission, successfully sending 480p (640×480) resolution video signals at a high rate of 1638.4 kbps with high

reliability from the transmitter to the receiver. However, the experimental setup was limited to 270° of phase operation, which restricts achieving a full 360° phase range.

In 2023, dual-polarized programmable metasurfaces played a role in green and secure communication. The metasurface schematic and unit structure are shown in Fig. 13(e), where a single-pole single-throw (SPST) switch is used to switch between x -polarization and y -polarization. Each polarization channel supports independent communication, effectively doubling the communication capacity. Additionally, QPSK and 8PSK information transmission were achieved, and Fig. 13(f) shows the constellation diagrams for the two polarization channels. Therefore, programmable metasurfaces enable multi-channel high-speed transmission by using phase modulation to simplify transmitter architectures¹⁸⁷.

QAM transmitter

Quadrature amplitude modulation (QAM) is a modulation technique that requires two independent amplitude-modulated signals with a phase difference of $\pi/2$. Compared to PSK modulation, QAM imposes higher hardware requirements, as it requires precise control of both the phase and the amplitude of the carrier wave. A metasurface-based QAM transmitter can control both the amplitude and phase of the carrier by adjusting the reflection coefficients of the metasurface, enabling advanced modulation schemes. In 2018, Dai et al.⁸³ designed a time-domain coded metasurface that allows for independent control of harmonic amplitude and phase. By adjusting the bias voltage of the metasurface units, periodic variations in harmonic amplitude can be achieved. Additionally, applying time delays to the switching functions of the metasurface units enables modification of the harmonic reflection phases, allowing the metasurface to reshape the wavefronts of multiple harmonics. Incorporating cyclic time delays for harmonic and phase control simplifies the design of the coded metasurface. To accommodate higher-order modulation schemes, in 2020, Dai et al.¹⁷² addressed this challenge by proposing an improved harmonic modulation scheme. This approach modulates information using specific harmonic frequencies to implement a 16QAM modulation scheme. The proof-of-concept prototype was designed for 4.25 GHz and experimentally validated in an indoor environment. Using the 16QAM modulation scheme, the actual transmission rate was increased to 10 Mb/s,

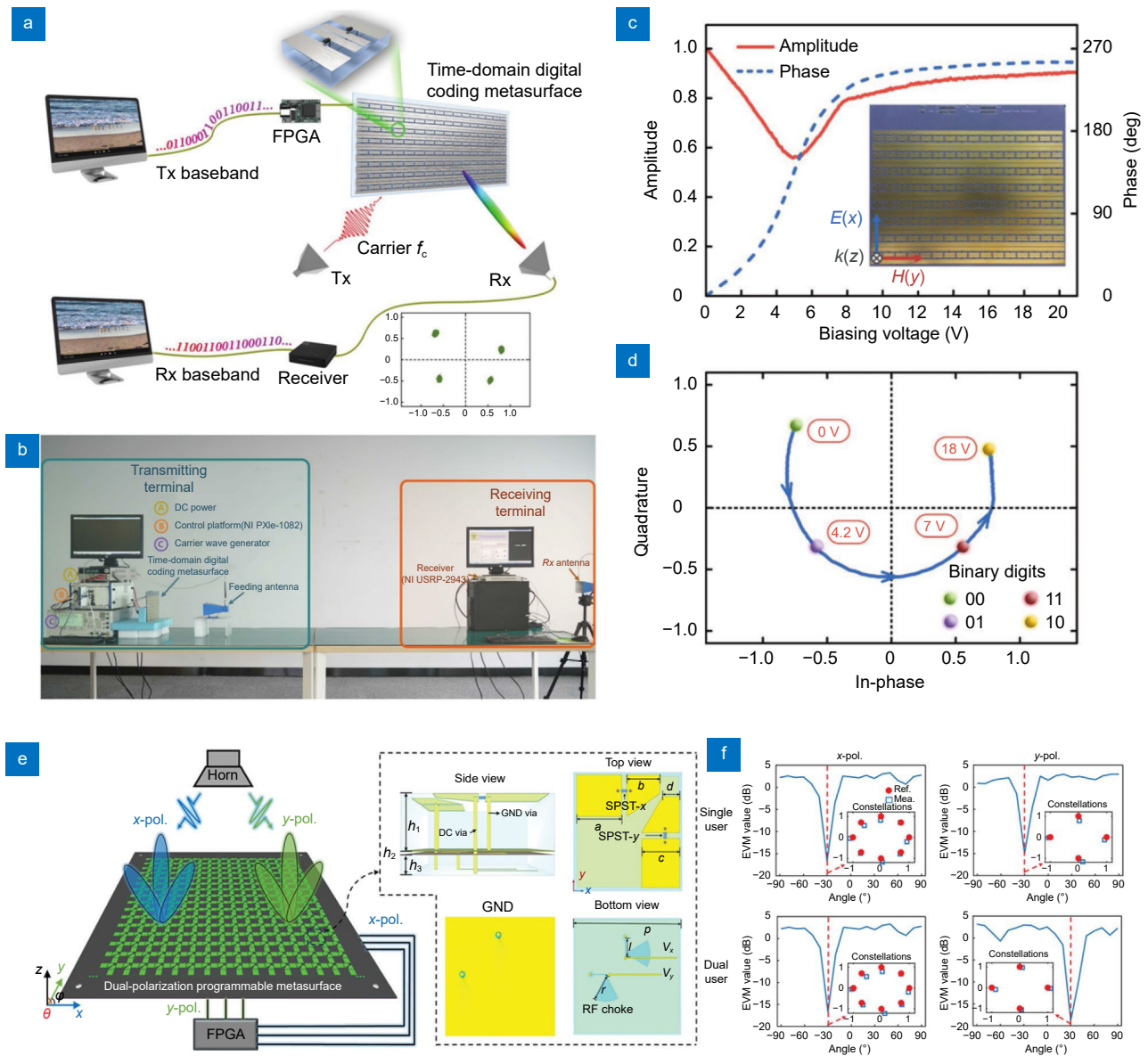


Fig. 13 | (a) Schematic of a wireless communication system based on a time-domain encoded metasurface. (b) Device for wireless communication using a time-domain encoded metasurface. (c) Measured amplitude and phase spectra of the metasurface at a frequency of 4 GHz. (d) In-phase and quadrature components of the reflection coefficient as a function of bias voltage. (e) Schematic diagram of dual-polarized metasurface communication. (f) EVM values of the dual-polarized metasurface in single-user and dual-user modes. Figure reproduced with permission from: (a–d) ref.¹⁸⁶, (e, f) ref.¹⁸⁷, John Wiley and Sons.

During the experiment, linearly varying phase waveforms were used as the fundamental functions for amplitude modulation. Additionally, time delays were introduced into the basic functions of phase modulation. Ultimately, the system successfully achieved various modulation schemes, including PSK, QPSK, and 16 QAM. Wang et al. proposed a high-order terahertz communication scheme utilizing on-off keying (OOK) modulation to achieve three types of high-order modulation schemes: QPSK, 16-phase shift keying (16-PSK), and 16-quadrature

amplitude modulation (16-QAM), as illustrated in Fig. 14(a). In high-order modulation, obtaining the constellation diagram is crucial. Figure 14(b) demonstrates the waveform of 16 transmission symbols (S1–S16) using different combinations of duty cycle and time delay, with different colors representing distinct symbols. Figure 14(c) further presents the constellation points at the +1st harmonic, where solid arrows indicate amplitude modulation induced by the duty cycle, while dashed arrows represent phase modulation caused by time delay.

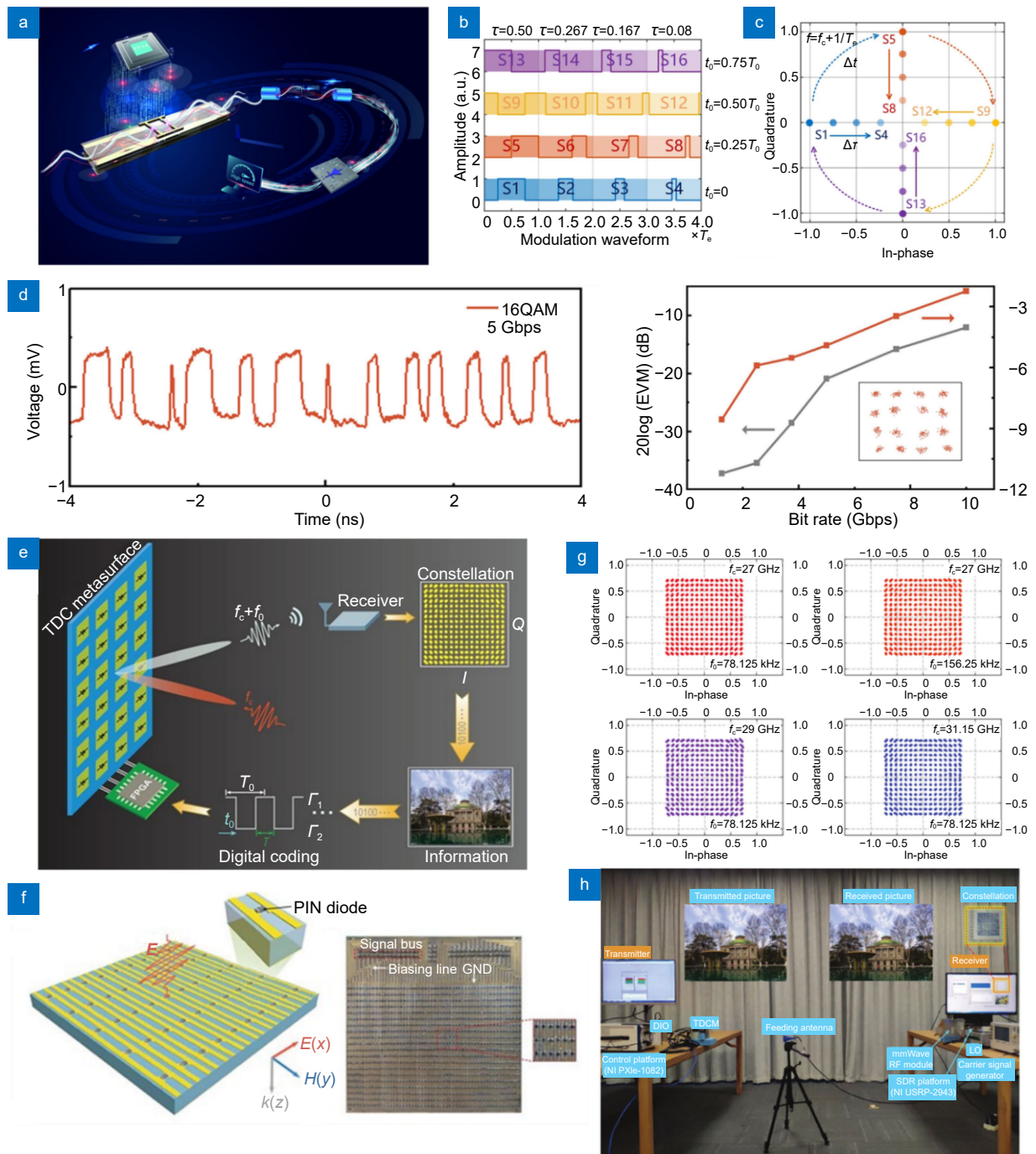


Fig. 14 | (a) Block diagram of a wireless communication transmitter based on TDCM. (b) Unit structure of TDCM. (c) Constellation diagram of the QAM transmitter under different modulation schemes measured using harmonic modulation. (d) Bit error rate comparison of QPSK, 8 PSK, and 16 QAM modulation schemes at two different symbol rates. (e) Conceptual diagram of a millimeter-wave wireless communication system based on TDCM. (f) Schematic diagram of a 1-bit TDCM and the unit structure with loaded PIN diodes. (g) Explanation of real-time indoor image transmission using a millimeter-wave 256 QAM transmitter. (h) Received constellation diagram of the millimeter-wave 256 QAM transmitter at different carrier frequencies. Figure reproduced with permission from: (a–d) ref.¹⁷², The AAAS; (e–h) ref.¹⁸⁸, Oxford University Press.

Theoretically, any constellation distribution can be synthesized through time encoding, enabling the realization of arbitrary high-order modulation schemes. Figure 14(d) shows the received 16-QAM waveform at a corre-

sponding bit rate of 5 Gbps.

Obviously, lower order modulation schemes have better performance due to their simpler constellations. As the modulation scheme becomes more complex, the

system's BER performance deteriorates because the control circuitry inevitably experiences reduced performance at higher modulation frequencies. To address this issue, in 2021, Chan et al¹⁸⁸ proposed a method using periodic square waves. By adjusting the duty cycle and time delay of the square wave waveform, precise control over harmonic amplitude and phase can be achieved, Fig. 14(e) is the conceptual diagram, and Fig. 14(f) shows the photograph of the metasurface and the schematic diagram of the unit structure with loaded PIN diodes. This method enables the implementation of a 256QAM modulation scheme at harmonic frequencies. A new digitally coded metasurface was developed in the Ka-band to create a prototype for a millimeter-wave 256QAM transmitter. Figure 14(g) shows the real-time indoor image transmission system at 27 GHz, and Fig. 14(h) displays the constellation diagrams measured at carrier frequencies of 27 GHz and 31.15 GHz. This demonstrates that the harmonic modulation method not only supports high-order modulation schemes but also produces standard constellation diagrams. This flexibility reduces the limitations of STC digital metasurfaces in combined amplitude and phase modulation. By precisely controlling the reflection coefficients, the metasurface-based QAM transmitter achieves synchronized control of both carrier amplitude and phase, offering a new technological approach for high-order modulation schemes. Compared to traditional transmitters, metasurface technology simplifies the architecture, reduces costs, and lowers power consumption. In the future, this technology holds significant potential for wireless communication in millimeter-wave and terahertz frequency bands, meeting the demands for higher transmission rates and lower bit error rates, and providing new possibilities for the advancement of wireless communication systems.

Direct radiation encoding metasurface wireless communication

Direct radiation metasurface wireless communication uses programmable coding metasurfaces to directly modulate digital information onto the metasurface. This approach generates various far-field scattering patterns, enabling efficient modulation and transmission of electromagnetic waves, with high security and elevated transmission rates.

In 2019, Cui et al⁸⁶ proposed a method for direct digital modulation (DDM) using programmable coding metasurfaces for digital information transmission. This

technique involves encoding digital information onto the metasurface using an FPGA. Electromagnetic waves are radiated onto the metasurface through a feeding antenna, and the far-field radiation pattern depends on the digital encoding sequence. A lookup table is established to relate far-field scattering patterns to digital codes, allowing modulation of digital signals through variations in these patterns. Multiple receivers positioned at different angles capture the far-field radiation patterns from the metasurface, and post-processing is used to recover the transmitted digital information, completing the direct transmission process.

Since the far-field radiation patterns are used to modulate digital information, the digital information can only be recovered from multiple locations rather than a single point, making the proposed DDM wireless communication system inherently secure without the need for additional encryption techniques. Figure 15(a) illustrates the architecture of the DDM system. The transmitted message is first divided into multiple n -bit binary codes, referred to as information codes, which are then mapped to m -bit hardware codes using a channel optimization algorithm. This algorithm ensures that each hardware code corresponds to a unique radiation pattern, thereby increasing the number of available digital states. The system controls the metasurface via column control, so the number of bits in the hardware code matches the number of independently controllable columns on the metasurface, with each encoded particle's digital state controlled by the hardware code. Figure 15(b–e) demonstrate the performance of the prototype system, where a black-and-white image is encoded and transmitted. During line-of-sight propagation, if a metallic obstacle is placed between the transmitter and receiver, the transmission process is interrupted; however, the channel optimization algorithm successfully recovers the transmitted image.

The structure of the metasurface unit is shown in Fig. 15(f), where the surface integrates PIN diodes and can achieve two states. At a working frequency of 10.15 GHz, it has an amplitude greater than 0.98 and a phase difference of 180° . This setup enables high-quality image information transmission, supporting a 2-bit transmission mode with an average transmission rate of 124 byte/s per second. When obstacles are present between the transmitter and receiver, the channel optimization algorithm can search for available digital states and reconstruct a new lookup table to continue information transmission.

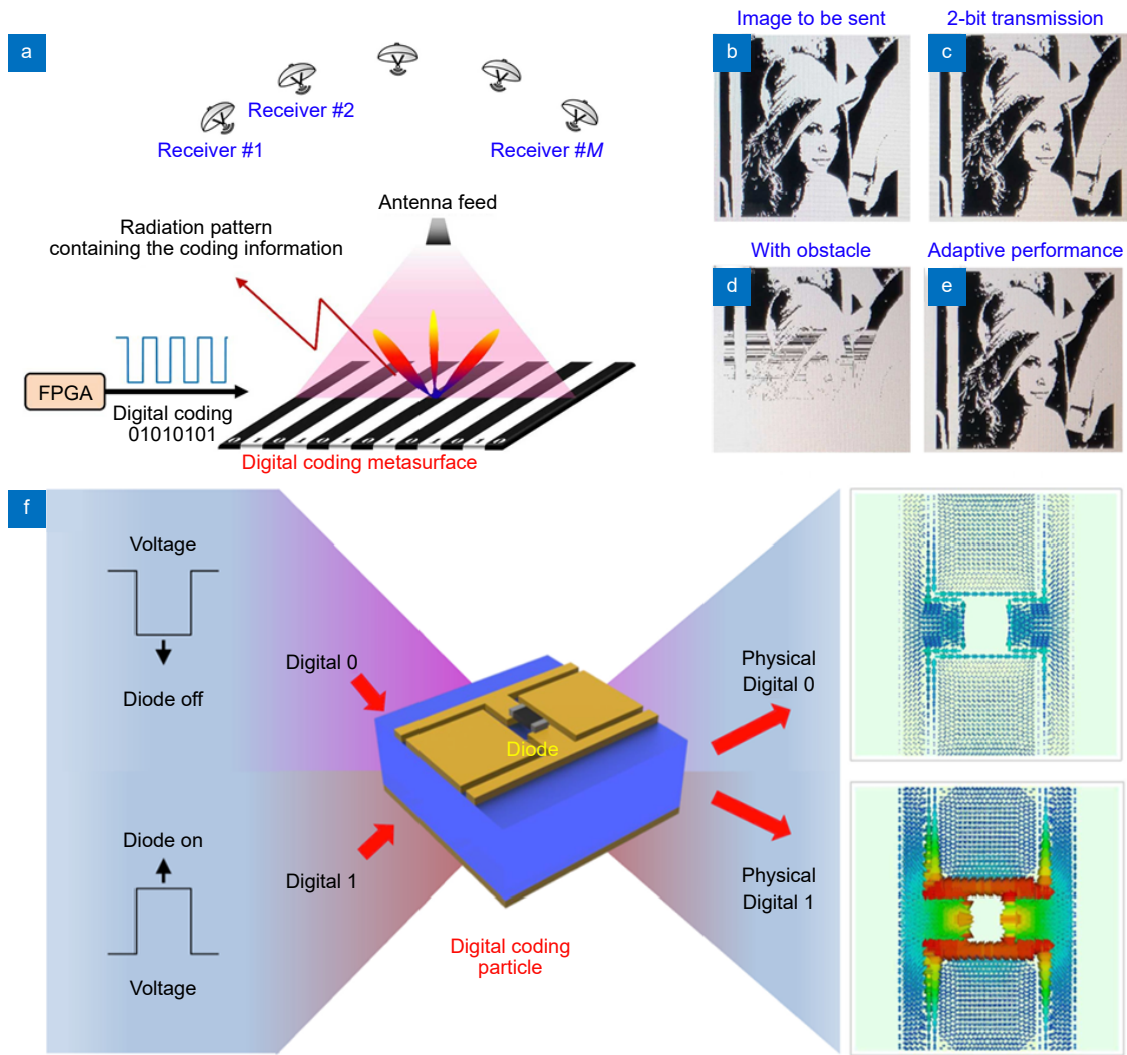


Fig. 15 | (a) Conceptual diagram of the programmable coded metasurface-based digital information system for direct transmission. (b–e) Transmission images and results of the DDM wireless communication system. (f) Unit structure of the encoding metasurface in the DDM system. Figure reproduced with permission from ref.⁸⁶, Oxford University Press.

In such cases, the quality of the transmitted image remains as good as in the previous scenarios. Theoretically, transmission speeds exceeding 100 Mbps are anticipated in practical applications.

Direct radiation metasurface wireless communication utilizes the programmable characteristics of metasurfaces to directly modulate digital information through far-field scattering patterns, achieving efficient and secure wireless communication. Compared to traditional methods, this technology simplifies system architecture and offers advantages of low cost and low energy consumption.

In the previous section, we introduced different types of coded metasurface-based transmitters, including FSK, PSK, and QAM transmitters, as well as direct radiation

coded metasurface communication. These architectures have their own advantages and disadvantages, making them suitable for different wireless communication scenarios. To further summarize their characteristics, we compare them in terms of modulation method, system architecture, hardware complexity, spectral efficiency, and applicable scenarios, as shown in Table 1.

From the table, it can be seen that FSK and PSK transmitters have relatively simple structures, making them suitable for low-power, short-range communication. In contrast, QAM transmitters offer higher spectral efficiency but at the cost of increased hardware complexity. Meanwhile, direct radiation coded metasurface communication provides an innovative information modulation method, directly modulating information through

Table 1 | Comparison of coded metasurface-based transmitter architectures and novel wireless communication systems.

Type	Modulation method	System architecture	Hardware complexity	Spectral efficiency	Application scenarios
FSK transmitter	Frequency shift keying (Utilizing resonance)	Metasurface reflection resonance to achieve information transmission at different frequencies	Low	Low	Low-power IoT, short-range wireless transmission
PSK transmitter	Phase shift keying (Utilizing dynamic phase control of metasurface)	Metasurface dynamic phase switching for direct modulation of reflected signals	Medium	Medium	Low-power short-range communication
QAM transmitter	Amplitude + Phase modulation (Utilizing metasurface to control reflection amplitude and phase)	Precise control of reflection amplitude and phase to achieve high-order modulation	High	High	High-speed data communication, such as 5G, Wi-Fi 6, and terahertz communication
Direct radiation coded metasurface communication	Modulation via Far-field scattering mode	Metasurface coding directly forms tunable scattering modes	Medium	Low	High-security wireless communication, smart wireless environments

scattering modes and reducing the need for traditional RF links.

Each type of coded metasurface transmitter has its own technical advantages and disadvantages, as detailed below: FSK transmitters: simple structure and low power consumption, but low spectral efficiency, making them unsuitable for high-speed communication. PSK transmitters: improve spectral efficiency while maintaining low power consumption but require higher phase control accuracy. QAM transmitters: capable of carrying more information within the same bandwidth, making them ideal for high-data-rate communication (e.g., 5G, Wi-Fi 6), but they require highly precise dynamic control of the metasurface, leading to increased hardware complexity. Direct radiation coded metasurface communication: enables multi-angle information modulation and enhances system security, but introduces challenges in receiver design and is more susceptible to environmental factors. Metasurface-based wireless communication systems have been applied in areas such as underwater communication¹⁸⁹, OAM high-capacity communication^{190,191}, terahertz wireless communication¹⁹², and visible light communication¹⁹³.

Multi-channel direct communication system

In 2019, Wan et al¹⁹⁴. proposed a multi-channel direct communication system based on information metasurfaces. This system can synthesize different near-field patterns to control the intensity of corresponding pixels on the focal plane. It uses three channels to transmit independent binary digital symbols defined by amplitude

codes. Each user at a specific location can have a separate channel and receive different information through amplitude modulation.

Figure 16(a) illustrates the multi-channel transmission system, where the transmission information of DCPM is described by a binary phase code matrix. Strong field intensity is represented by the digital symbol "1", and weak field intensity by "0". The phase codes are stored in an FPGA to control DPCM. Different binary symbols can be transmitted at different near-field points, enabling multi-channel direct transmission of near-field information.

The binary amplitude shift keying (BASK) modulation scheme is used to independently modulate the information for three channels. The eight coding modes in Fig. 16(b) are assigned to correspond to each possible digital information of the three channels. Three receivers are deployed at specified orientations to receive information, and the information is demodulated in their respective wireless channels.

In 2023, Zheng et al¹⁹⁵. introduced a multi-channel transmission scheme for dual-frequency direct wireless communication, which utilizes a spatially multiplexed, multi-level amplitude programmable metasurface. This innovative approach allows for dual-channel communication across two separate frequency bands, significantly enhancing transmission efficiency. By employing ASK for modulation, the system enables programmable control of the metasurface's far-field amplitude, thereby achieving a multi-bit amplitude modulation scheme.

Figure 16(c) illustrates a schematic for transmitting

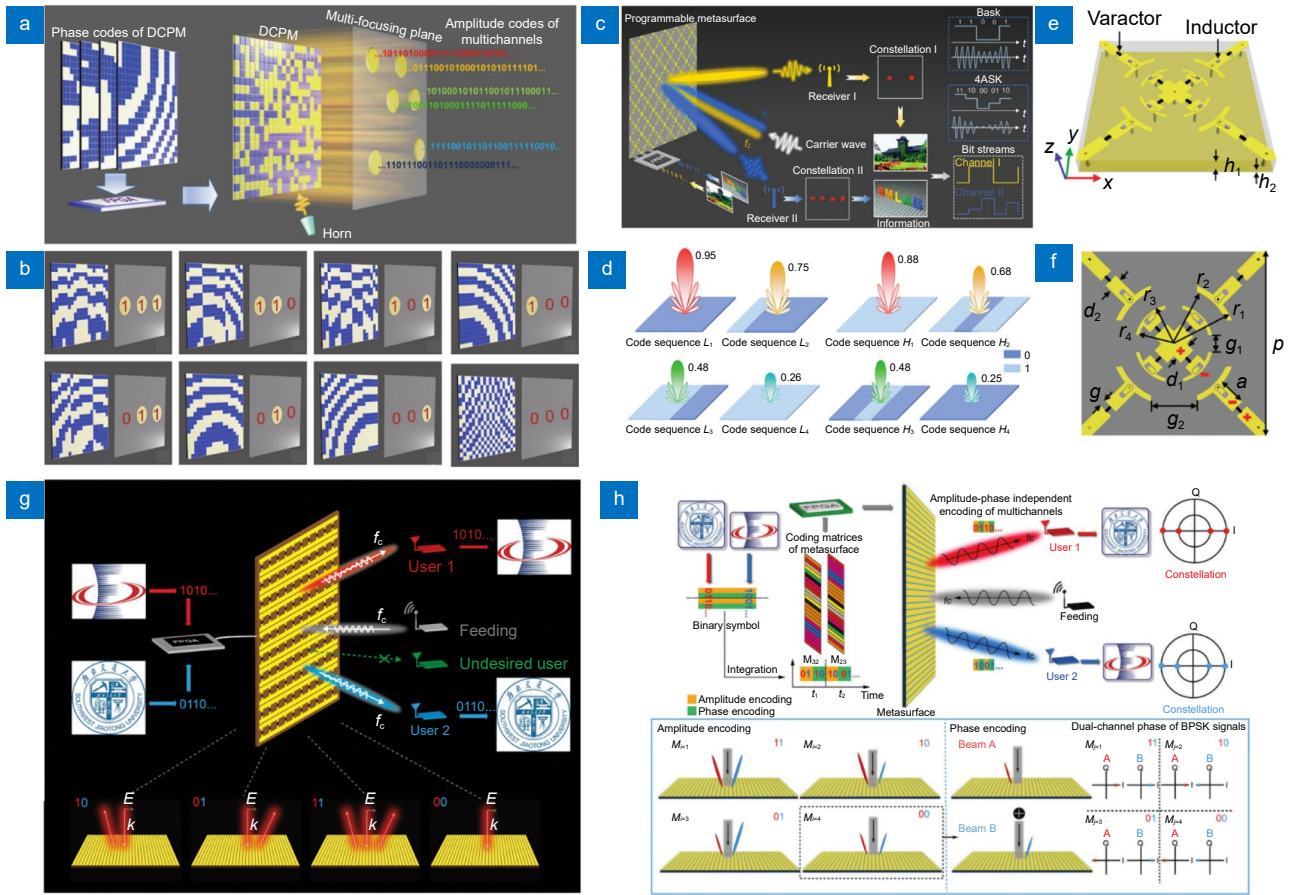


Fig. 16 | (a) Multi-channel transmission system based on metasurfaces. (b) Eight coding patterns for three-channel direct transmission using the metasurface. (c) Dual-band multi-bit wireless communication system assisted by metasurfaces. (d) Reflection amplitude of the metasurface with different coding sequences at 3.58 GHz and 5.24 GHz frequencies. (e, f) Basic unit structure of the metasurface and its magnified view. (g) Conceptual diagram of a dual-channel wireless communication system using spatially coded beamforming metasurfaces. (h) Conceptual diagram of spatial division multiplexing wireless communication based on metasurfaces. Figure reproduced with permission from: (a, b) ref.¹⁹⁴, Springer Nature; (c–f) ref.¹⁹⁵, (g) ref.¹⁹⁶, (h) ref.¹⁹⁷, John Wiley and Sons.

two pieces of information simultaneously via the metasurface. Different bit streams from the FPGA module are applied to the metasurface using two distinct operating frequencies, f_1 and f_2 . The incident carriers at f_1 and f_2 can be modulated independently using BASK and 4ASK modulation schemes, respectively, to transmit different images. On the right, the bit streams corresponding to the BASK and 4ASK modulation schemes are shown, demonstrating that the transmission efficiency of 4ASK is twice that of BASK within the same period. Channel I uses BASK, while Channel II employs 4ASK. These modulation schemes are received and demodulated into images by different receivers.

Figure 16(d) shows the unit structure of the metasurface. The outer ring is connected to adjacent units, while the inner ring is completely separated from the outer ring and is connected to the central bias pattern via var-

actor diodes. The vias distributed along the diagonal connect to a metal ground plane, with each varactor diode matched to a via. The inner and outer rings can independently generate dynamic responses at two different operating frequency bands, specifically 3.58 GHz and 5.24 GHz. Figure 16(e) and 16(f) display the reflection amplitude responses of the metasurface under different bias voltages and frequencies.

The metasurface enables two independent transmission channels by altering the conduction states of the inner and outer ring diodes, facilitating the transmission of information using BASK and 4ASK modulation schemes. The encoding strategies for the two frequency channels are distinct. At 3.58 GHz, a "0" corresponds to a high reflection amplitude, resulting in an increased reflection amplitude of the metasurface with the number of "0s". Conversely, at 5.24 GHz, a "1" represents a high

reflection amplitude, making the reflection amplitude response dependent on the number of "1s". Consequently, even with the same encoding sequence applied to the metasurface, the reflection amplitude response varies between the two different frequency states. The working frequencies of the two transmission channels can be selected by switching the conduction states of the inner and outer ring diodes. The measured reflection phase remains nearly constant and can be considered negligible during the demodulation process. Additionally, the experimental setup demonstrated that increasing the distance between the metasurface and the receiving antenna from 1.0 meters to 2.6 meters did not significantly impact the transmission performance. In the experiments, the maximum transmission rate achieved in Channel I, operating at 3.58 GHz, was 312.5 kbps, while Channel II, operating at 5.24 GHz, reached a transmission rate of 625 kbps. Although the symbol transmission rates are equivalent to the bit rates in BASK modulation, the bit rate in 4ASK modulation is twice that of BASK modulation. This effective increase in transmission speed highlights the enhanced capability of the metasurface-based system.

Programmable metasurfaces in multi-channel wireless communication are not limited to a single modulation mode. Metasurfaces that modulate both phase and amplitude offer better performance in suppressing side-lobe gain. As shown in Fig. 16(g) and 16(h), amplitude-phase programmable metasurfaces not only enable simultaneous multi-channel information transmission but also reduce information leakage^{196,197}.

Communication systems based on intelligent metasurfaces

Metasurfaces have made significant progress in manipulating electromagnetic waves, enabling the realization of the rich functionalities mentioned earlier, with notable breakthroughs in the time domain, frequency domain, and spatial domain. However, as the applications of metasurfaces continue to expand, the design methodologies must keep pace with the evolving needs of the field. Traditional design processes typically involve model design, parameter scanning, and optimization. The use of optimization algorithms often requires dozens or even hundreds of EM simulations, which is both time-consuming and computationally expensive. Therefore, the design of metasurfaces should gradually evolve toward diversification, integration, and programmability, sim-

plifying the design process and reducing design time to prevent significant resource wastage.

In automation and computation, deep learning, as a branch of machine learning, can simulate human cognitive and learning processes, thereby simplifying repetitive and complex tasks¹⁹⁸.

In 2018, Zhang et al.¹⁹⁹ proposed the use of machine learning to design anisotropic metasurfaces. They employed machine learning algorithms to enable intelligent design of metasurfaces. The study used deep neural networks to model the design space of the metasurface, learning the mapping relationship between complex electromagnetic properties and design parameters. During the optimization of metasurface coding patterns, the system could automatically explore optimal solutions within a large-scale design space. Traditional machine learning algorithms, such as Support Vector Machines (SVM) and Decision Trees, were also utilized to classify and predict the performance of specific design schemes, assisting in the optimization process. Through efficient coding design, they achieved anisotropic control of electromagnetic waves. The paper also verified the accuracy of the encoding, showing a phase response accuracy of 90.05%, with a 360° phase error of only 2°. The 1-bit anisotropic metasurface designed using deep learning was able to realize three functionalities: dual-beam scattering, circular polarization, and linear polarization, as well as triple-beam scattering. This allowed the metasurface to flexibly control the polarization states and scattering modes of multiple beams.

In 2019, Qiu et al.²⁰⁰ proposed a deep learning-based metasurface design method called REACTIVE. This method uses deep learning to establish the relationship between metasurface structures and their EM properties, as shown in Fig. 17(a) and 17(b). Specifically, the approach involves training a deep learning model using a set of sample data, enabling it to reveal the underlying patterns between metasurface structures and their electromagnetic responses. The use of deep neural networks (DNN) allows for the automation of metasurface design, which differs from traditional metasurface design methods, as illustrated in Fig. 17(c). Simulation results show that the REACTIVE model achieves an average accuracy of 76.5%, with the accuracy exceeding 90% for the top 30% of the samples. Using the REACTIVE method, the researchers designed a multi-band absorber. By inputting the desired absorption rate, the deep learning model could automatically generate the corresponding

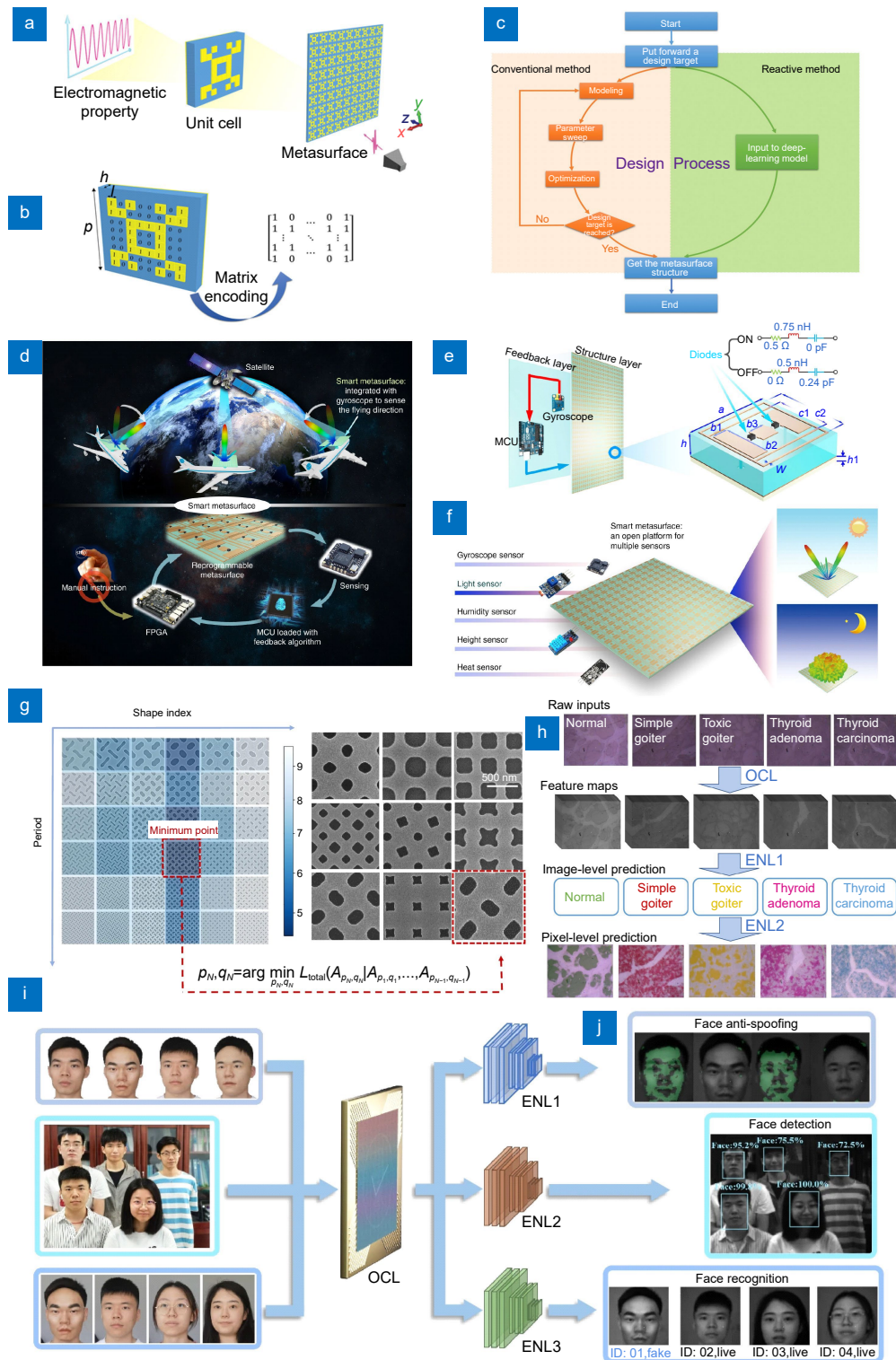


Fig. 17 | (a) Concept diagram of automatic metasurface design. (b) Unit structure and encoding matrix diagram. (c) Comparison flowchart of REACTIVE method and conventional metasurface design methods. (d) Smart metasurface with adaptive reprogramming functionality and microcontroller system diagram. (e) Smart metasurface unit structure and its diode equivalent circuit model. (f) Metasurface integrated with multiple sensors and its application in light control. (g) Gradient-based metasurface topology optimization (GMTO) algorithm. (h) Pathological tissue slice. (i, j) By modifying the electronic network layer (ENL), the same SCNN chip can be trained to perform face anti-spoofing, face detection, and face recognition tasks. Figure reproduced with permission from: (a–c) ref.²⁰⁰, John Wiley and Sons; (d–f) ref.²⁰¹, (g–j) ref.²⁰², Springer Nature.

metasurface structure. During the design process, the trained model takes the absorption rate as input and outputs the matching metasurface structure. The design achieved three absorption peaks at 6.1 GHz, 17.3 GHz, and 19.1 GHz, with absorption rates of 67%, 93%, and 99.7%, respectively, which were in high agreement with the preset design goals.

Compared to traditional design methods, the REACTIVE approach improved the design process speed by 200 times, significantly reduced the computational load, and enhanced the accuracy of the design results.

Traditional metasurface designs are typically programmed according to fixed design goals, and once completed, the metasurface cannot be dynamically adjusted in response to environmental changes or task requirements. This limitation restricts their application in dynamic and complex environments. In 2019, Ma et al.²⁰¹ proposed an intelligent metasurface with adaptive reprogramming capabilities. This metasurface can automatically reconfigure based on external conditions, offering dynamic adjustment abilities. Figure 17(d) shows the system schematic. To achieve this functionality, the study introduced intelligent algorithms and reprogrammable mechanisms to alter the phase, amplitude, or polarization state of the metasurface units, enabling the metasurface to adjust its electromagnetic response in real-time. Figure 17(e) illustrates the unit structure and spatial model with loaded diodes.

In the experiment, the researchers developed a motion-sensitive intelligent metasurface integrated with a three-axis gyroscope. This metasurface can adaptively adjust the radiation direction of electromagnetic waves based on different rotational angles. Additionally, an online feedback algorithm was used as the control software, enabling the intelligent metasurface to achieve dynamic responses, such as steering single or multiple beams, further enhancing its adaptability and flexibility. Figure 17(f) demonstrates its functionality in optical control.

In 2022, Ma et al.²⁰³ explored how to extend the functionality of metasurface design using statistical machine learning (SML) methods. The study leveraged machine learning techniques to enhance the metasurface's capability to multiplex across multiple electromagnetic tasks, enabling a single metasurface to simultaneously perform various functions, such as beamforming, polarization control, and frequency selection. The research introduced a multi-functional design framework that allows a metasurface to achieve multiple electromagnetic func-

tions at the same time. This framework integrates machine learning models into both gradient-based and non-gradient optimization cycles, enabling the automatic design of multi-functional metasurfaces. By using statistical learning algorithms, metasurface design can learn the relationships between unit structures and their electromagnetic responses from extensive training data, allowing the prediction of the overall performance of the metasurface. In terms of unit design, the study adopted data-driven methods to enhance design efficiency by optimizing structural parameters.

To achieve functionality multiplexing, the research applied high-dimensional search algorithms to explore the metasurface design space and optimize the balance and combination of different functions. Unlike traditional two-step methods like phase retrieval or metamaterial design, the proposed end-to-end framework utilizes the full design space, pushing multi-functional design capabilities toward their physical limits. The experimental results demonstrated the practical application of this approach. The researchers successfully created an easy-to-manufacture, single-layer metasurface lens and hologram, which achieved up to 8 controllable responses in the near-infrared region. These responses were influenced by the working frequency and the combination of linear polarization states, a performance level that traditional design methods could not achieve. This approach marks a significant advancement in the field by enabling metasurfaces to function in a multi-dimensional and versatile way, opening up new possibilities for applications in communication, imaging, and sensing.

In 2022, the team led by academician Cui TJ from Southeast University, in collaboration with professor Li LL from Peking University, used a multilayer transmissive digital coding metasurface to construct a real-time adjustable diffractive neural network, successfully achieving real-time programming of network parameters and optical-speed computation¹⁵⁶. The article describes the use of a multilayer transmissive digital coding metasurface to implement field-programmable microwave-driven diffractive neural network hardware, called a programmable artificial intelligence machine (PAIM). PAIM dynamically controls the amplitude and phase of electromagnetic waves through transmissive metasurface units to simulate the behavior of neurons in the human brain in regulating signals. The propagation of electromagnetic waves in free space also establishes the connections and communication between different

layers of units, equivalent to the connections between neurons.

Currently, artificial intelligence is realized mainly through two technologies: one is computer-based machine learning algorithms (such as deep learning²⁰⁴, extreme learning²⁰⁵, and reinforcement learning²⁰⁶), and the other is dedicated integrated circuit chips or specialized optical computation chips^{207,208}. To improve integration and versatility, diffractive neural networks are inevitably evolving toward multifunctional integration and programmability, leading to the proposal of the PAIM. The system uses a five-layer transmissive programmable metasurface array to hierarchically control the spatial propagation and interaction characteristics of electromagnetic waves. Each layer of the metasurface array has 8×8 units, with each unit considered a neuron node in an artificial neural network (ANN). The entire PAIM can be viewed as a physical implementation of an ANN. Each metasurface unit can control the amplitude of transmitted electromagnetic waves in the range of -22 dB to 13 dB, while also adjusting the phase coupled with the amplitude.

When the incident electromagnetic wave hits a programmable metasurface unit, the amplitude and phase of the wave are modulated by that metasurface unit, with control coefficients directly managed by an FPGA. The modulated electromagnetic wave then radiates in various directions after passing through the unit. Each unit in the first layer of the metasurface array radiates electromagnetic waves to the second layer, where the waves undergo vector addition. The summed waves serve as the incident electromagnetic waves for each unit in the second layer, which are modulated and propagated in the same manner until they reach the fifth layer. The output from the fifth-layer metasurface is taken as the final output of the entire PAIM. The process of controlling the electromagnetic wave propagation through each layer of the metasurface array in the physical network can be viewed as the forward computation process in a neural network.

In the communication encoding-decoding case, the research team demonstrated real-time encoding, decoding, and denoising based on PAIM. PAIM directly performs signal encoding, decoding, and denoising operations in the electromagnetic wave simulation domain and can simultaneously transmit four user signals over the same channel. To increase the transmission speed, different parts of the image are transmitted through dif-

ferent user channels, which results in a transmission speed four times faster than the original. In the reinforcement learning experimental case, through continuous interaction and self-learning with the electromagnetic environment, PAIM focuses the randomly distributed incident electromagnetic wave energy onto one predetermined target point.

In 2025, Cui et al.²⁰² proposed a spectral convolutional neural network (SCNN) with metasurface-assisted imaging, integrating spectral filtering and convolution operations directly within the sensor. This approach leverages the high-efficiency spectral modulation capabilities of metasurfaces.

By utilizing an integrated SCNN framework, sensor-edge computing is achieved under incoherent natural light. This framework enables real-time detection of natural 3D data cubes with both spatial and spectral features while performing optical analog computing, as illustrated in Fig. 17(g). The computation speed and power consumption of the optical convolutional layer (OCL) depend solely on the exposure time and the power of the CMOS image sensor, enabling ultra-fast and energy-efficient optical computing.

Based on this, materials can be distinguished. Furthermore, by modifying the electronic network layers (ENLs), the same SCNN chip can perform tasks such as pathological diagnosis, as shown in Fig. 17(h), and face anti-spoofing detection, as depicted in Fig. 17(i) and Fig. 17(j).

Programmable metasurfaces can also be integrated with electroencephalography (EEG) control technologies for the development of brain-machine interfaces, enabling remote mental control of metasurfaces. The event-related potentials from EEG can be non-invasively converted into digital encoded information in the electromagnetic domain, which can then be processed and transmitted automatically and wirelessly through the information metasurface²⁰⁹.

Additionally, in 2023, Jiang et al.¹⁴¹ proposed a metasurface design that combines intelligent target sensing and adaptive beamforming with dual functionality, as shown in Fig. 18(a). The metasurface consists of multiple superatoms, each containing two PIN diodes and a sensing channel structure, capable of achieving polarization-insensitive and programmable beamforming and target sensing functions. The metasurface unit structure is illustrated in Fig. 18(b). By controlling the switching states of the PIN diodes, these superatoms provide a

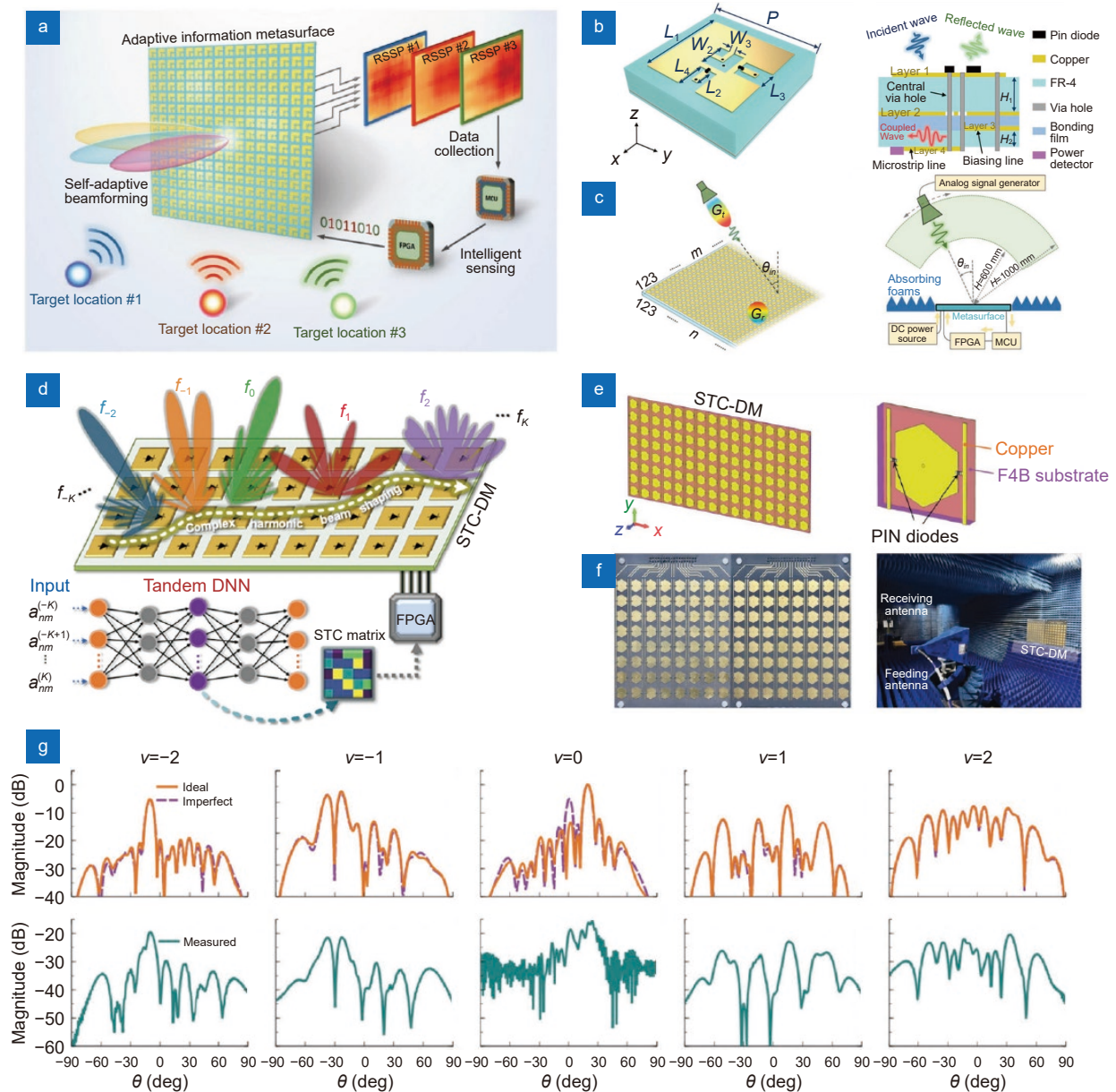


Fig. 18 | (a) Schematic of the adaptive information metasurface. (b) Structure of the metasurface unit and illustration of the EM wave. (c) Theoretical electromagnetic model of the information metasurface and the experimental setup for DNS estimation. (d) DNN-driven multi-frequency beamforming STC-DM metasurface. (e) Metasurface model and unit structure. (f) Prototype of the metasurface and experimental setup. (g) Experimental verification of joint synthesis at the 5th harmonic frequency. Figure reproduced with permission from: (a–c) ref.¹⁴¹, John Wiley and Sons; (d–g) ref.²¹⁰, John Wiley and Sons

1-bit phase response within the designed frequency band, with sensing loss consistently maintained above -10 dB, ensuring minimal interference between the beamforming and sensing functions.

Experimental results show that the designed metasurface can simultaneously achieve intelligent target sensing and adaptive beamforming, with measurement results closely matching numerical simulations and theoretical calculations. Figure 18(c) shows the theoretical

electromagnetic model of the information metasurface and the experimental setup for DNS estimation. Specifically, the simultaneous functions of programmable reflections and sensing (SFPRS) units function as efficient 1-bit reflective phase modulators, reflecting most of the incident wave in two states while maintaining a 180° phase difference. Meanwhile, part of the incident wave is captured by the top metal pattern, converted into guided waves through metal holes, and fed into the bottom RMS

power detector. The input power of the detector is linearly related to the output voltage, allowing the received signal strength to be calculated from the output voltage.

In the experiment, a microcontroller unit collects the received signal strength from each SFPRS unit in the array, constructing a 2D map of received signal strength in space, which is used to estimate the location of the incident power source. Based on these sensing data, a FPGA can execute various intelligent applications. To validate the metasurface's intelligent sensing and adaptive beamforming capabilities, experiments were conducted to test the positioning accuracy of a near-field power source and the far-field directional pattern of adaptive beamforming in an indoor environment. Based on these real-time sensed positioning data, the metasurface achieved adaptive beamforming through appropriate digital encoding. The experiment further validated the metasurface's ability to shape beams in the far field. The measured far-field directional pattern showed that the -3 dB beamwidth was able to cover the expected deflection angle, thus demonstrating the effectiveness of the proposed electromagnetic-sensing-based adaptive beamforming concept.

In 2024, Rossi et al.²¹⁰ proposed a novel multi-frequency synthesis method for space-time coding digital metasurfaces (STC-DMs) based on machine learning (ML), as shown in Fig. 18(d). The metasurface unit structure and experimental setup are illustrated in Fig. 18(e) and 18(f). By using a serial DNN architecture, the required equivalent current distributions at different harmonic frequencies are directly mapped to the coding sequences of universal superatoms. The advantage of this method lies in its ability to effectively decouple the multi-frequency synthesis problem, allowing the application of traditional semi-analytical array design techniques for harmonic beamforming and control, and enabling precise customization of amplitude and phase distributions.

Under the new STC-DM framework, the significant integration of ML with semi-analytical techniques allows the method to achieve complex scattering patterns that could not be accomplished by existing design methods. Meanwhile, the computational complexity is essentially independent of the size of the STC-DM. This method not only solves the multi-frequency synthesis problem but also overcomes the limitations of traditional designs, enabling more complex electromagnetic functionalities. As shown in Fig. 18(g), experimental results from the -2 to $+2$ order confirm that the scattering lev-

els for five frequency modes remain approximately 10 dB below the maximum value, demonstrating that the designed metasurface can independently manipulate scattering modes at multiple frequencies.

Although coding metasurfaces have demonstrated tremendous potential in wireless communications, their large-scale deployment still faces challenges in manufacturing and integration. Firstly, the fabrication of large-scale coding metasurfaces is technically demanding. As the number of metasurface elements increases, achieving high-precision, low-cost mass production remains a significant bottleneck. This is particularly true in the millimeter-wave and terahertz frequency bands, where extremely high structural precision is required during manufacturing. Traditional photolithography and electron-beam etching techniques are costly, limiting the large-scale production of metasurfaces. Secondly, the integration of active components and power consumption issues pose additional challenges. While active devices such as PIN diodes and varactor diodes enable dynamic tunability, they also incur higher power consumption. This becomes especially critical when controlling large arrays, where overall energy consumption may become a limiting factor. Furthermore, the long-term stability of active devices, thermal management, and compatibility with metasurface substrate materials also affect practical applications. In the future, reducing manufacturing costs while improving the integration and reliability of metasurfaces will be key research directions for advancing coding metasurface communication technologies toward practical applications.

Metasurface-based vortex vector light field communication

Compared to traditional plane waves, vortex light has higher degrees of freedom and can carry more information. The phase distribution of vortex beams exhibits a helical pattern, with zero light intensity at the vortex center. As the vortex aperture increases, the light intensity gradually increases towards the outer regions. Each photon in a vortex beam possesses OAM $l\hbar$,⁴⁶ where l represents the topological charge and $\hbar$ denotes the reduced Planck constant. For a vortex beam with a phase factor $\exp(il\theta)$, each photon can carry $l\hbar$ of OAM. Vortex beams with different topological charges carry different orbital angular momenta, and these states are orthogonal to each other, ensuring they do not interfere. In communication research, information can be encoded onto

different states. Due to the mode orthogonality of vortex beams with different topological charges, information transmission remains interference-free, making this approach valuable for high-capacity communication applications^{160,211–219}.

Vortex vector optical field communication combines vortex vector light with metasurfaces, enabling information transmission based on metasurfaces. In such a communication system, vortex vector light serves as the information carrier, while the metasurface, utilizing its unique structural properties, is used to encode and decode the transmitted information. We will elaborate on the application of metasurfaces in vortex vector optical field communication from the perspectives of passive and active metasurfaces.

Principles and techniques of vortex vector optical field communication

Polarization vortices and phase vortices are two important concepts in vortex light communication. Both involve the rotational characteristics of light waves, but they have different roles and significance in this

context⁸⁷. A polarization vortex refers to the rotation of the polarization state of a light wave along its propagation direction. This phenomenon occurs when the polarization direction of the electromagnetic wave rotates as the light wave travels. Based on the direction of polarization, polarization vortices can be classified into transverse magnetic (TM) and transverse electric (TE) polarizations. By controlling the polarization state of the light wave, polarization vortices can transmit additional information, leading to higher transmission rates and enhanced security. Polarization vortices are typically generated using vortex polarization generators or through nonlinear optical effects.

Figure 19 shows the radial polarization beam (TM_{01}) and the transverse electric beam (TE_{01}) in Fig. 19(a) and 19(b), respectively. These beams exhibit polarization singularities at their centers, as illustrated by the circular electric field intensity distribution.

Phase vortices refer to the rotational structure of the phase distribution of a light wave along its propagation direction. On a cross-section, the light wave's phase exhibits a rotating structure used for encoding and

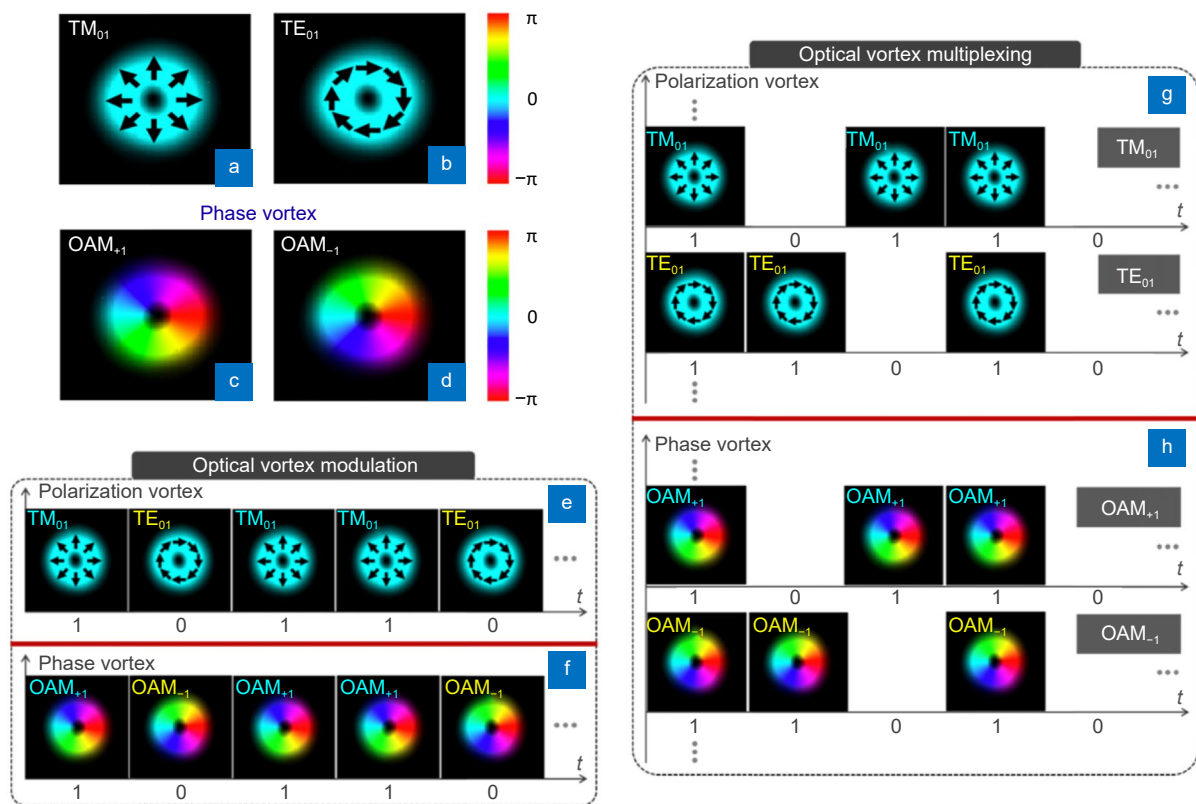


Fig. 19 | (a, b) TM_{01} and TE_{01} polarized vortex beam. (c, d) Phase vortex field distributions for $OAM = -1$ and $+1$. (e) Polarization vortex modulation. (f) Phase vortex modulation. (g) Polarization vortex multiplexing. (h) Phase vortex multiplexing. Figure reproduced with permission from ref.⁸⁷, under a Creative Commons Attribution License.

transmitting information. Phase vortices are typically generated and controlled using spatial light modulators or interferometers. [Figure 19\(c\)](#) and [Fig. 19\(d\)](#) illustrate the phase distributions of two OAM modes: -1 and $+1$, each featuring a phase singularity at the center.

In vortex light communication, OAM modulation and OAM multiplexing can be employed. For OAM modulation, different data can be represented by various polarization vortex states in time-varying polarization vortex modulation. Binary encoded information can be represented by two polarization vortex states: TM_{01} represents the code "1", and TE_{01} represents the code "0", as shown in [Fig. 19\(e\)](#). Similarly, this mapping approach can be applied to phase vortex modulation, where different phase vortex beams correspond to different codes, as illustrated in [Fig. 19\(f\)](#).

In OAM multiplexing, vortex beams with different polarizations are used as independent channels, with the presence or absence of polarized vortex beams corresponding to different digital codes. For example, in the TM_{01} channel, the presence or absence of the polarized vortex beam corresponds to the digital codes "0" and "1", respectively, and a similar coding pattern applies in the TE_{01} channel, as shown in [Fig. 19\(g\)](#). Utilizing polarized vortex beams for multi-channel multiplexing can enhance transmission capacity and spectral efficiency. The same multiplexing technique is also applicable to phase vortex beams, as demonstrated in [Fig. 19\(h\)](#). By leveraging multiple OAM beams, transmission capacity can be continuously increased, and spectral resources can be fully utilized.

Passive metasurface vortex vector optical field communication

When dealing with n -order harmonics, vortex vector beams ensure that the harmonic signal wavelength is exactly $1/n$ of the fundamental beam wavelength. This grants the light additional tunability, potentially enhancing communication and information encoding capabilities. However, it is challenging to achieve high nonlinear conversion efficiency since the helical phase needs to be transferred to n harmonic signals simultaneously²²⁰.

In 2020, Zhao et al.²²¹ proposed a method to achieve high-efficiency second harmonic vortex beam generation using a metallic metasurface. This technique combines nonlinear materials with a metallic metasurface to produce harmonic vortex beams.

They utilized gold nanoholes to excite an optical field

with vortex phase distribution, thereby enhancing the conversion efficiency of the OAM signal. Using the Pancharatnam-Berry (PB) phase principle, they applied an additional phase with a topological charge of l to the incident left-hand circularly polarized light (LHCP) and a corresponding topological charge to the right-hand circularly polarized light (RHCP) without vortex phase, resulting in an LHCP component with a $2l$ phase. At different harmonic orders n , after passing through a single layer of WS_2 , the RHCP is no longer considered, and the final vortex beam will have a topological charge of $2nl$. Comparing the spectra of the Au- WS_2 structure and the pure WS_2 structure at 405 nm, showing that the light intensity of the Au- WS_2 structure is nearly four times that of the pure WS_2 , indicating a significant enhancement effect. The wavelength is half of the fundamental wave, consistent with second harmonic generation characteristics. In 2020, Stella et al.²²² proposed a novel mechanism for generating vortex beams through free-space radiation, where OAM is achieved via the diffraction of excited Bloch surface waves (BSWs), as illustrated in [Fig. 20\(a\)](#). A circularly polarized laser beam is tightly focused on the multilayer surface using an immersion optical element, causing the TE-polarized BSW to radially emit from the focal point. The experimental setup is shown in [Fig. 20\(b\)](#).

Large-capacity free-space communication using OAM beams requires multiplexing and demultiplexing techniques for various OAM modes. In 2016, Li et al.²²⁴ proposed a highly integrated off-axis technique for multiplexing and demultiplexing multiple OAM, wavelength, and polarization channels. Light beams without OAM characteristics can be transmitted at different incident angles to coaxial beams with different OAM characteristics. Coaxial beams carrying multiple OAM characteristics can be split into different directions using the fundamental mode. Additionally, components based on dipole optical antenna metasurfaces can serve as OAM and polarization multiplexers/demultiplexers, enabling efficient multiplexing and demultiplexing of multiple channels. In 2020, Li et al.²¹⁹ further utilized off-axis technology and the spin Hall effect of light to achieve multiplexing and demultiplexing of 10 channels containing OAM and spin angular momentum. The demultiplexing efficiency for all angular momentum (AM) states exceeded 8%, with maximum crosstalk between AM states at -12.8 dB. Furthermore, the output light was focused on the focal plane, which can be directly coupled into a single-mode

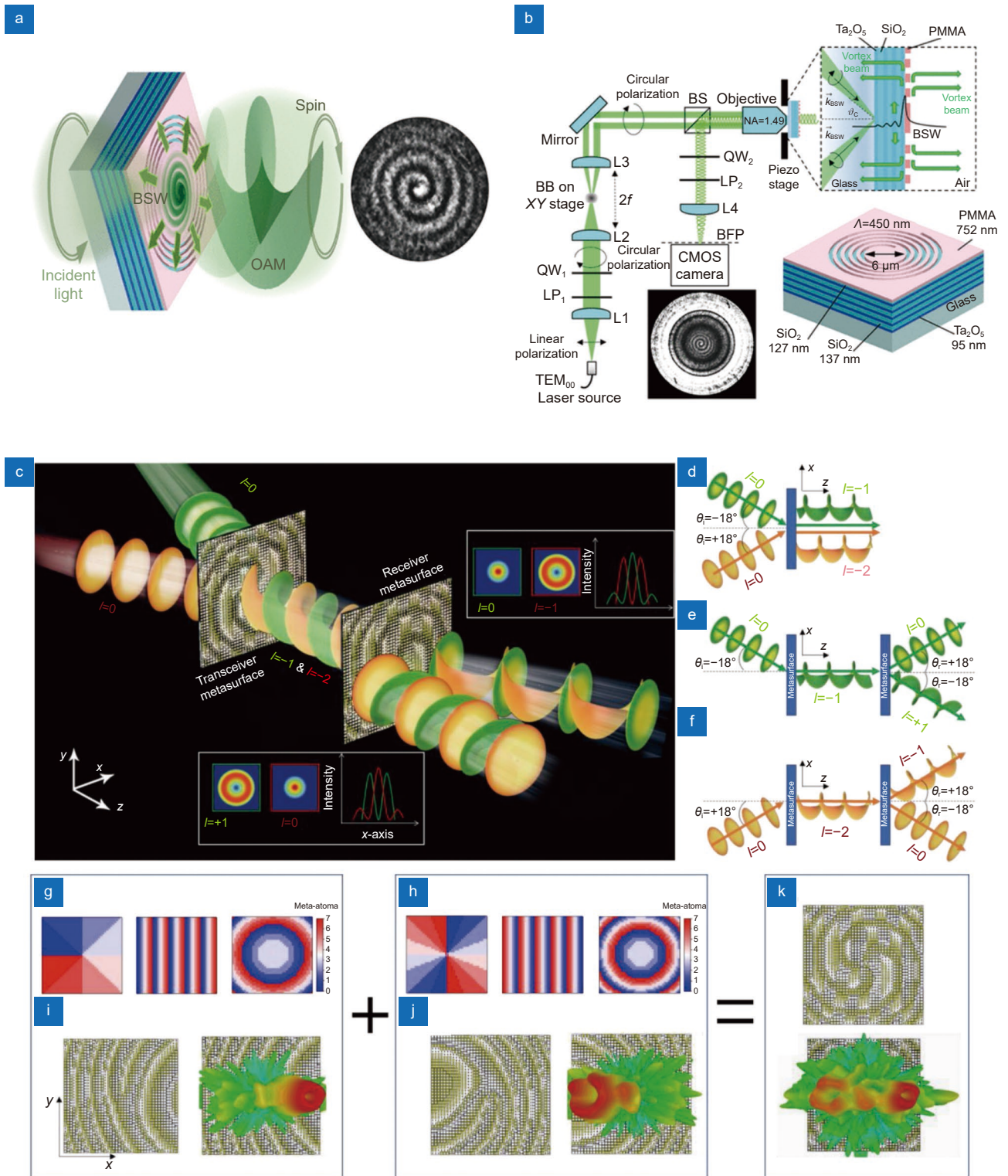


Fig. 20 | (a) Schematic diagram of the metasurface structure. (b) Schematic diagram of the vortex beam generation device. (c) Schematic of OAM multiplexing and demultiplexing based on a pair of metasurfaces with identical designs. (d) Schematic of generating OAM beams with $l = -1$ and -2 using a transceiver metasurface. (e, f) Schematic of incident Gaussian beams transforming through the transceiver and receiver metasurfaces at incident angles of -18° and $+18^\circ$. (g, h) Phase mode diagrams of OAM modes $l = -1$ and -2 . (i-k) Metasurface structure and simulated far-field patterns of the generated OAM beams. Figure reproduced with permission from: (a, b) ref.²²², under a Creative Commons Attribution License; (c-k) ref.²²³, John Wiley and Sons.

waveguide, offering a compact system design.

In 2022, Chung et al.²²³ proposed and experimentally demonstrated the use of a single metasurface structure for OAM multiplexing and demultiplexing at E-band frequencies (83 GHz). The metasurface design incorporates a helical phase pattern for generating OAM modes, a one-dimensional gradient phase pattern for off-axis beam integration and splitting, and a lens phase pattern to reduce the divergence angle of the vortex beam, as shown in Fig. 20(c). Two linearly polarized off-axis Gaussian beams with different incident angles are converted by the metasurface into coaxial OAM beams with $l = -1$ and -2 , aligned in the vertical transmission direction (z -axis), as depicted in Fig. 20(d). The $l = -1$ vortex beam forms a Gaussian beam and an $l = +1$ OAM beam at refraction angles of $+18^\circ$ and -18° , respectively, as shown in Fig. 20(e). Similarly, the $l = -2$ vortex beam forms an $l = -1$ OAM beam and a Gaussian beam at refraction angles of $+18^\circ$ and -18° , respectively, as shown in Fig. 20(f).

To achieve vortex beams, they integrated three phase patterns into the metasurface design and applied lens phase patterns to reduce the divergence angle of vortex beams caused by the inherent divergence of Gaussian beams, as shown in Fig. 20(g) and Fig. 20(h). Vortex beams with orbital angular momentum modes $l = -1$ and -2 were generated, as illustrated in Fig. 20(i) and Fig. 20(j). Finally, these metasurface designs were integrated into a single design for OAM multiplexing, producing far-field patterns under normal incidence, as depicted in Fig. 20(k). This dielectric metasurface can control the OAM states of light waves in the E-band, enabling multiplexing and demultiplexing. This implies that vortex light communication technology can transmit more data in the E-band and, through demultiplexing, separate different data streams, making communication systems more flexible and efficient.

Compared to the visible light spectrum, research on vortex beams in the terahertz band has lagged behind. The primary challenge lies in the dependency between the divergence angle of vortex beams and the topological charge number, which limits the modulation of vortex beams^{225,226}. To address this issue, in 2022, Gu et al.²²⁷ proposed the concept of quasi-perfect vortices. This concept is based on the geometric phase principle and employs a dielectric subwavelength unit structure with polarization-insensitive characteristics. By combining staggered arrangements and phase superposition principles,

they achieved a beam divergence angle that is independent of the topological charge number.

Figure 21(a) illustrates the generation of double-channel ordinary vortex beams with one topological charge, as shown on the left. The surface distribution of the metasurface is the superposition of phase profiles φ_A , φ_B , and φ_C , where $\varphi_A = \pm 2\pi x/P$ represents the phase profile for beam deflection, and φ_B and φ_C represent the vortex beam generation and focusing, respectively. Regarding the generation of dual-channel perfect vortex beams (Q-PVBs), as shown in Fig. 21(b), the phase of the metasurface consists of four parts, enabling simultaneous steering of two focused vortex beams with different topological charges in opposite directions.

Based on the above research methods, they designed a multifunctional metasurface to generate dual-channel quasi-perfect vortex beams. A partial unit structure is shown in Fig. 21(c). This metasurface can simultaneously generate $+1$ and -1 order quasi-perfect vortex beams within the 0.75–0.9 THz frequency range and deflect them in opposite directions. All quasi-perfect vortex beams exhibit a typical annular electric field intensity distribution, as shown in Fig. 21(d). The multifunctional metasurface for four-channel quasi-perfect vortex beams, under the incidence of a fundamental Gaussian beam, can simultaneously produce ± 1 and ± 2 order quasi-perfect vortex beams. The beam spot diameter remains consistent and maintains a complete annular electric field distribution within the measurement range, as illustrated in Fig. 21(e), demonstrating excellent control over the divergence angle. Compared to vortex beams with the same topological charge, Q-PVBs exhibit reduced light divergence and offer better control over beams with high topological charges, which is of significant importance in the field of wireless communication.

To further expand communication capacity, high-dimensional orthogonality of OAM modes can be utilized for high-speed multiplexing of vortex optical signals. This approach enhances communication capabilities by multiplexing OAM modes, polarization, and wavelength. A common method is to load a cross-shaped grating phase onto a geometric phase metasurface to achieve OAM mode multiplexing. However, this method's polarization-insensitive modulation characteristics limit its ability to handle OAM mode and polarization dimension multiplexing simultaneously, and the lack of polarization-dependent phase modulation restricts its multi-channel polarization performance. To address these

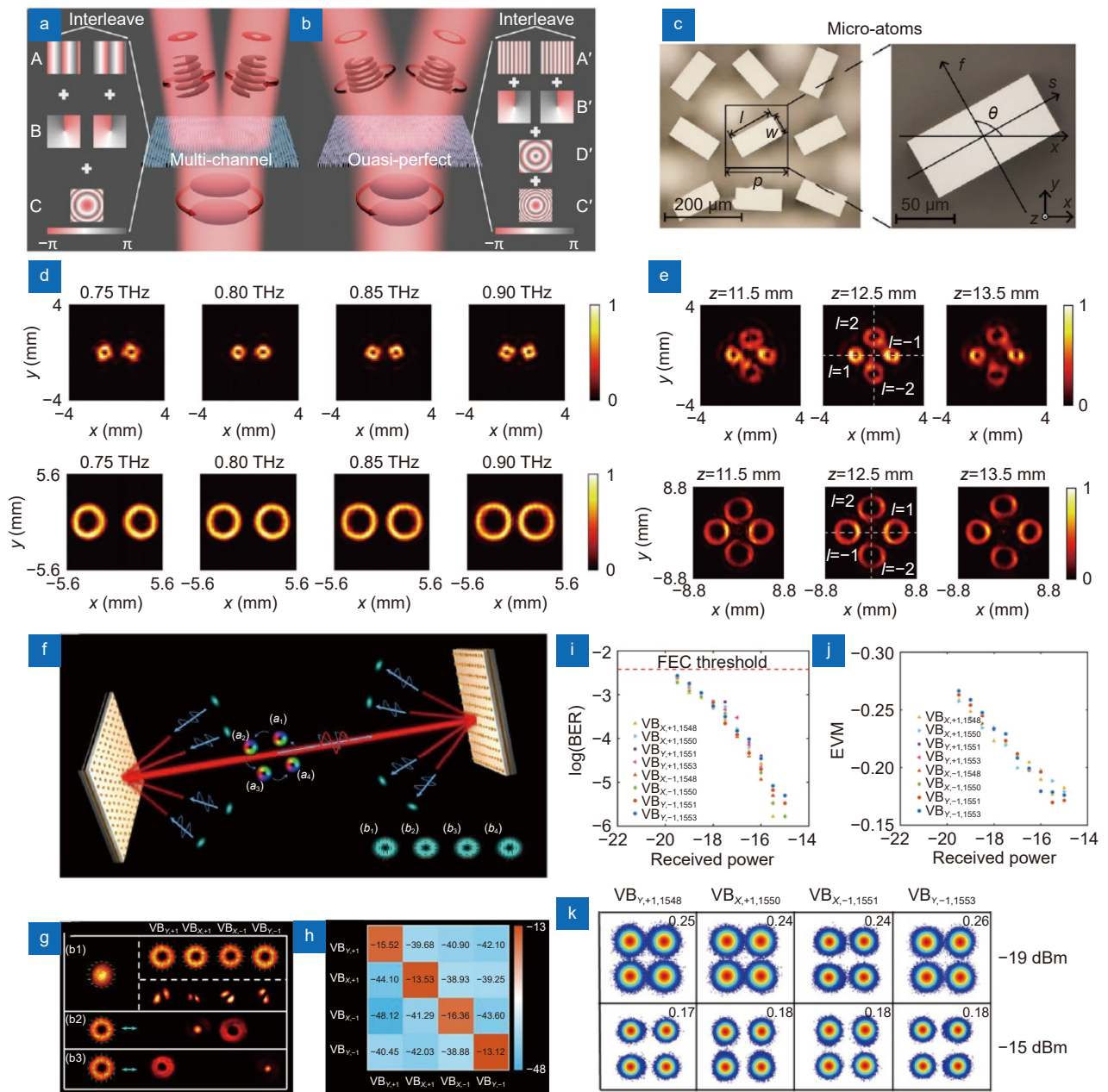


Fig. 21 | (a) Generation of multi-channel vortex beams using all-dielectric metasurfaces with synthesized phase. (b) Near-perfect vortex beam generation using all-dielectric metasurfaces with synthesized phase. (c) Partially magnified optical image of the metasurface unit. (d) Measured optical field intensity of dual-channel vortex beams and perfect vortex beams at different frequencies. (e) Measured optical field intensity of four-channel vortex beams and perfect vortex beams at different transmission distances. (f) Schematic diagram of OAM mode and polarization channel multiplexing. (g) Polarization and intensity distribution for each diffraction order under different incident beams. (h) Light intensity at the center of each diffraction order for different OAM beams; experimental results of OAM mode, polarization, and wavelength multi-dimensional joint multiplexing communication. (i) BER under different received power levels. (j) Error vector magnitude (EVM) under different received power levels. (k) Constellation diagram under different received power levels. Figure reproduced with permission from: (a–e) ref.²²⁷, (f–k) ref.²²⁸, under a Creative Commons Attribution License.

issues, in 2023, Li et al.²²⁸ proposed a high-capacity vortex optical multiplexing communication technology based on polarization-sensitive phase control metasurfaces. The study utilized the geometric phase extension

principle to design a "metal-dielectric-metal" metasurface. This metasurface has independent phase control capabilities for the orthogonal linearly polarized components of the optical field, effectively achieving joint

multiplexing of OAM modes and orthogonal linear polarization, as shown in Fig. 21(f).

They achieved independent phase modulation of the orthogonal linear polarization components of the light field by adjusting the orientation angle of the metasurface units. Additionally, they loaded two diffraction grating phases with orthogonal linear polarization responses onto the metasurface, effectively realizing the combined control of OAM modes and orthogonal linear polarization. When Gaussian light is incident on the metasurface from different diffraction orders, it can generate vortex beams with different OAM modes and linear polarization states. These beams are then combined into coaxial output beams along the zeroth diffraction order, achieving both OAM mode and linear polarization multiplexing. Subsequently, the coaxial beams are incident on another identical metasurface, where beams from different channels are restored to Gaussian light at specific diffraction orders, enabling the joint demultiplexing of OAM modes and linear polarization. Figure 21(g) shows the measured light intensity and polarization distribution, with y -polarized light filtered by linear polarizers. The energy along the matrix diagonal reflects the signal energy in the demultiplexed channels, as shown in Fig. 21(h).

They designed a 16-channel vortex light multiplexing communication system, incorporating two OAM modes, two linear polarization states, and four wavelengths, and successfully achieved 400 Gbit/s transmission of QPSK signals. The results show an error rate of 1.67×10^{-6} , as depicted in Fig. 21(i) and 21(j). Therefore, the proposed polarization-dependent phase modulation metasurface can achieve joint multiplexing of OAM modes and polarization, as shown in Fig. 21(k), and is compatible with wavelength division multiplexing technology to realize multi-dimensional joint multiplexing. This is advantageous for OAM communication and high-capacity dense communication.

In 2022, Yuan et al.²²⁹ proposed a super-atom metasurface based on the phase-change material $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST) that can redirect vector fields and generate vortex light with topological charges of 0, 1, and -1 . They introduced a metasurface composed of super-atom molecules consisting of four super-atom units.

By utilizing the large refractive index contrast between the amorphous (a-state) and crystalline (c-state) phases of the phase-change material GST, multifunctional tunability and rapid switching capabilities of the de-

vice can be achieved. Among the eight types of super-molecules composed of specific meta-atoms, the transmission polarization angles of the fourth and seventh types of meta-atoms are 49.59° and 139.60° , respectively, which are orthogonal to each other. By adjusting the states of these meta-atoms, a metasurface with a cross-shaped grating structure can be designed, which in turn can generate vortex beams with topological charges of 0, 1, and -1 . A metasurface composed of 80×80 super-molecules successfully generates vortex beams with different OAM orders under the illumination of normally incident x -polarized light. Compared to a single type of meta-atom, the design using a tetrad of meta-atoms offers more tuning parameters, thereby increasing the degree of freedom in modulation. This design not only ensures efficient modulation capability of the metasurface for vortex beams but also facilitates multi-channel and high-capacity communication. This approach demonstrates unique advantages in designing multi-state and multifunctional devices, offering new possibilities for the advancement of future communication technologies.

Active metasurface vortex vector light field communication

Programmable metasurfaces can utilize FPGA and PIN diode control circuits to perform a range of functions on vector light fields, including cross-line polarization, right circular polarization, left circular polarization conversion, scattering manipulation, diffusion, dual-band radiation, low cross-polarization emission, and OAM generation. Therefore, programmable metasurfaces are of significant importance for achieving multi-mode dynamic OAM beam modulation. In 2016, Han et al.²³⁰ designed a 1-bit encoded OAM beam generator, which utilizes PIN diodes to alter the resonant states of the metasurface unit cells, thereby controlling vortex beam generation in a reflective manner. They also revealed that the number of OAM modes produced is related to the size of the metasurface. This programmable reflective metasurface can not only generate multi-mode OAM beams by adjusting the bias voltage of the varactor diodes in the metasurface units, but it can also transmit multifunctional vortex light according to external dynamic requirements, thus increasing the information transmission capacity.

In 2020, Li et al.²³¹ proposed a programmable scattering metasurface that achieved various functions including OAM generation, as shown in Fig. 22(a). Different encoding sequences output by the FPGA control the

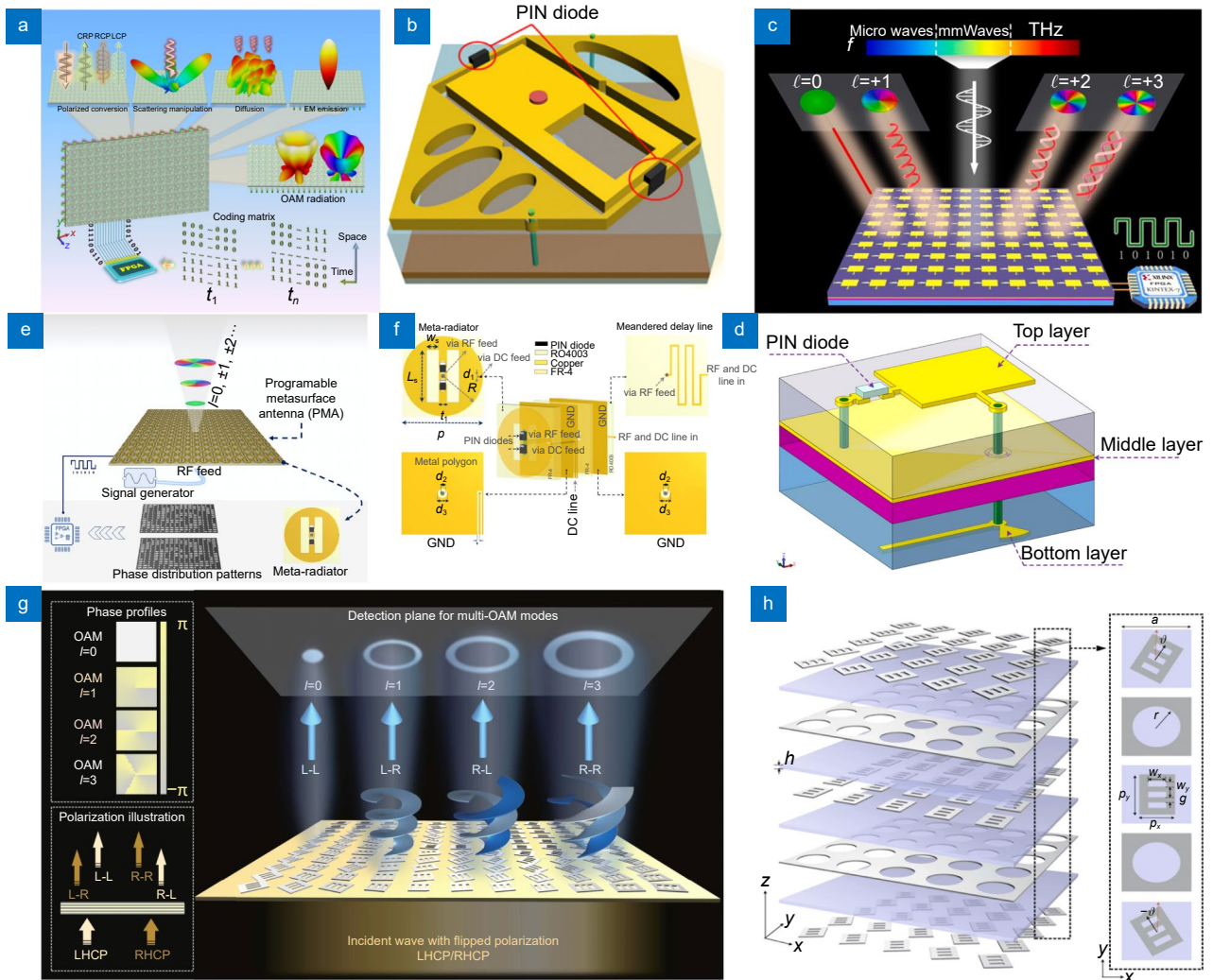


Fig. 22 | (a, b) Schematic diagram of OAM beam generation based on scattering programmable metasurfaces and its unit structure. (c, d) Schematic diagram of a programmable mmWave metasurface for dynamic OAM beam generation and its metasurface unit structure. (e, f) Schematic diagram of a programmable metasurface for simultaneous transmission of multi-mode OAM beams and its unit structure. (g, h) Schematic diagram of a metasurface for generating four-channel vortex beams using circularly polarized light and its unit structure. Figure reproduced with permission from: (a, b) ref.²³¹, John Wiley and Sons; (c, d) ref.²³², under a Creative Commons Attribution License; (e, f) ref.²³³, (g, h) ref.²³⁴, Springer Nature.

metasurface units, applying different voltages to the PIN diodes on the metasurface to adjust the amplitude, phase, and polarization state reflection coefficients. The metasurface unit structure is illustrated in Fig. 22(b), with copper and other metallic materials designed as a grounding layer to ensure good circuit grounding. Additionally, ports are connected to transmitting patches and metallic grounding to control the metasurface units. The metasurface units are preset to function as equivalent quarter-wave plates, with diode switches creating phase differences. When y -polarized light is incident, this design can generate OAM beams with topological charges of +2 and −2. Figure 23(a–d) presents simulated results

in the near field, demonstrating ideal generation effects and clear spatial phase distributions. In 2022, Liu et al.²³⁵ proposed a broadband reconfigurable metasurface that also utilizes "0" and "1" encoding for the dynamic generation of vortex beams.

In 2022, Bai et al.²³² proposed a programmable metasurface operating in the millimeter-wave band. By manipulating the units of the metasurface, they achieved dynamic multimode millimeter-wave vortex beams, as shown in Fig. 22(c). By modulating the bias voltage of the PIN diodes in the metasurface units via encoded signals from an FPGA, real-time control of vortex beams can be achieved. This allows for the generation of vortex

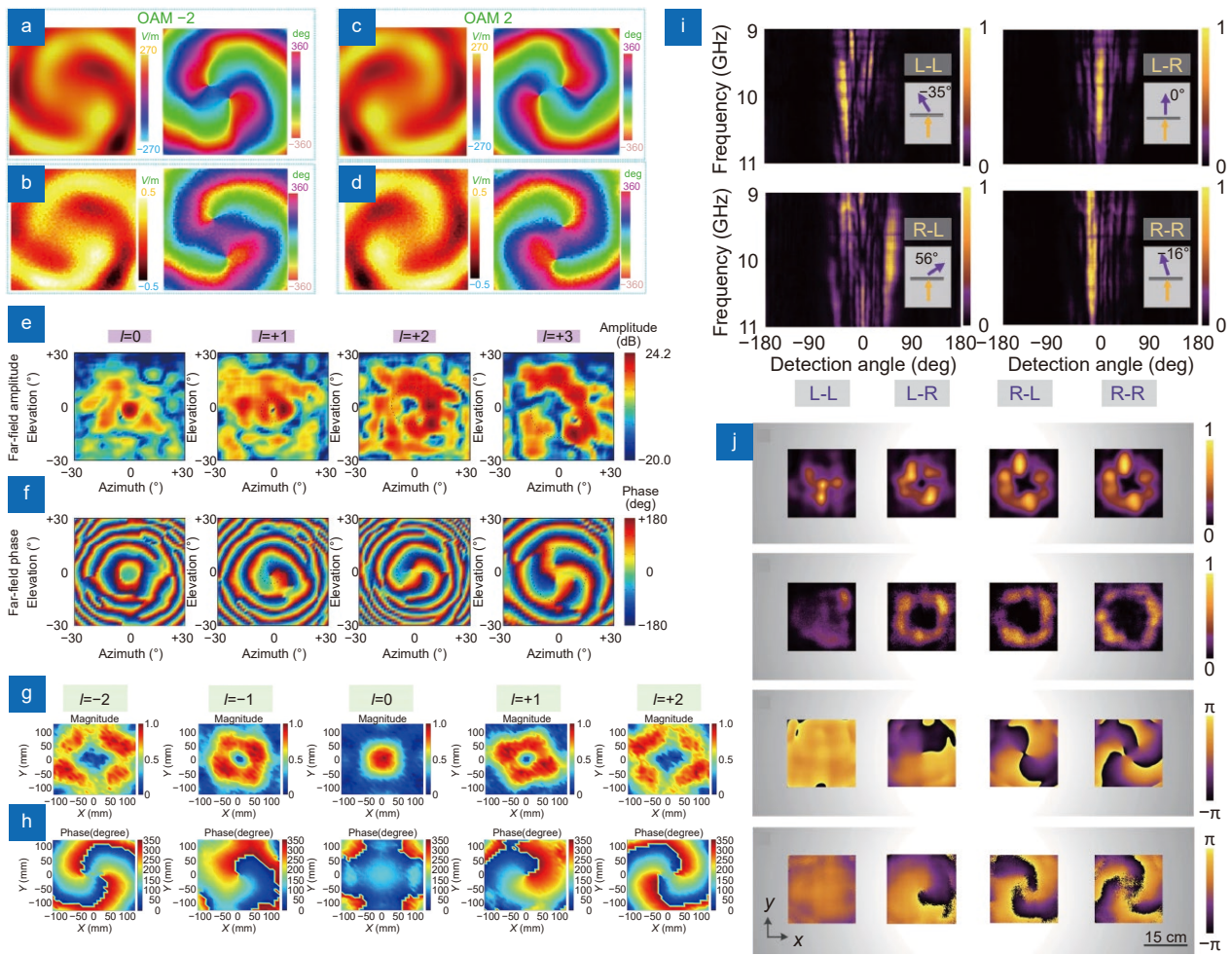


Fig. 23 | (a–d) Schematic diagram of programmable metasurfaces achieving OAM beam switching with different topological charges, including light intensity and phase distribution. (e, f) Experimental results of the far-field amplitude and phase for metasurfaces with different OAM modes. (g, h) Measurement of the magnitude and phase distribution of the near electric field on a planar surface for different modes. (i) Measurement of the normalized far-field intensity at different detection angles for frequency bandwidths (9–11 GHz) and channel configurations L-L-L, R-R-L, and R-R. (j) Energy intensity and phase distribution of output vortex beams carrying different OAM modes in the xoy plane. Figure reproduced with permission from: (a–d) ref.²³¹, John Wiley and Sons; (e–f) ref.²³², under a Creative Commons Attribution License; (g, h) ref.²³³, (i, j) ref.²³⁴, Springer Nature.

beams with OAM modes $l=0$, $l=+1$, $l=+2$, and $l=+3$. The structure of the metasurface unit is shown in Fig. 22(d). The unit comprises three layers of copper foil and a PIN diode. To minimize the impact on high frequency performance, the DC bias lines are placed in the center of the non-radiating patch edges.

The experimental results show that for OAM modes $l=0$, $l=+1$, $l=+2$, and $l=+3$, the area of the non-radiative zone of the vortex beam increases with the number of OAM modes. Additionally, for the four OAM modes, the measured gain of the zero mode beam reached 24.2 dB, and the aperture efficiency exceeded 20.9%. As the OAM number increases, the number of phase reversals also increases, as illustrated in Fig. 23(e, f). This indicates that

the designed metasurface achieves excellent performance in generating vortex beams, capable of producing vortex beams with different OAM numbers based on varying encodings, thus offering advantages in electromagnetic wave manipulation. Within the frequency range of 28–30 GHz, the metasurface demonstrates precise control over vortex light, and its dynamic performance is crucial for real-time communication and dynamic scenarios in millimeter-wave communication systems. In specific applications, it can dynamically adjust the properties of OAM beams to meet different communication needs and environmental changes.

In 2023, Nadi et al.²³³ proposed using a 1-bit programmable metasurface to generate multimodal OAM

beams, capable of simultaneously transmitting multiple independent OAM beams. At the operating frequency of the 6 GHz band, the programmable metasurface with 16×16 units can produce three-mode adjustable vortex beams, including OAM modes $l=0$, $l=\pm 1$, and $l=\pm 2$.

The metasurface unit features a four-layer metal structure, as shown in Fig. 22(e). The top layer consists of two rectangular metal patches connected by a PIN diode, as shown in Fig. 22(f). By loading the simulated radiation codes and mode distributions for four OAM modes into the metasurface units via FPGA, the electric field and phase distributions for the four modes can be obtained, as shown in Fig. 23(g, h). It can be seen that the amplitude distribution of the non-zero modes is hollow, and from the phase distribution diagrams, the number of phase reversals matches the OAM mode number, indicating that it shares the characteristics of vortex beams carrying OAM. Therefore, the 1-bit programmable metasurface can generate OAM beams with 360° helical phase in both "-" and "+" directions. By generating multi-mode OAM beams, multiple independent data streams can be transmitted simultaneously within the same communication system, thus enhancing the system's throughput and performance. Additionally, using the dynamic tuning capability of the programmable metasurface, multi-bit metasurfaces can achieve higher capacity information transmission²³⁶.

Transmission-type metasurfaces typically exhibit higher optical efficiency compared to reflection-type metasurfaces. In transmission-type metasurfaces, light passes through and is modulated, whereas in reflection-type metasurfaces, light must be reflected, leading to greater optical loss. Furthermore, transmission-type metasurfaces often have more applications and can achieve more complex optical functions, such as modulating interference patterns and generating vortex beams of different modes. This makes transmission-type metasurfaces more flexible and customizable in vortex vector optical field communication. In 2020, Bai et al.²³⁷ proposed a transmission-type programmable metasurface capable of generating multi-mode OAM beams. The metasurface units maintain good transmission efficiency even under oblique incidence. For the OAM mode $l=0$, the measured gain of the vortex beam exceeds 25.68 dB, demonstrating the high efficiency of the transmission-type programmable metasurface.

To achieve the transmission function of multi-mode OAM beams, it is necessary to extend the channels to

control OAMs with different topological charges. In 2020, Yuan et al.²³⁴ proposed and fabricated a polarization metasurface based on PB phase for modulating co-polarized and cross-polarized channels. By changing the circular polarization state at the input and output ends, arbitrary and independent wavefronts were achieved, as shown in Fig. 22(g). Through different circular polarization light channels, LHCP and RHCP generated OAM beams with four topological charges of $l=0, 1, 2$, and 3 in the two cross-polarized (L-R, R-L) and two co-polarized (L-L, R-R) directions.

The metasurface unit structure, as shown in Fig. 22(h), consists of five metal layers and four dielectric layers. Under LHCP illumination in the 9–11 GHz band, the co-polarized channel is tilted at -35° , while the cross-polarized channel remains undeflected. Under RHCP illumination, the co-polarized and cross-polarized channels are tilted at 58° and -16° , respectively. This indicates that different channels can produce different transmitted waves, as illustrated in Fig. 23(i). Through energy and phase measurements, as shown in Fig. 23(j), each polarization channel corresponds to different topological charges (L-L for 0, L-R for 1, R-L for 2, R-R for 3). The radius of the energy ring increases with the topological charge, which aligns with the energy distribution and phase patterns of vortex light with different topological charges. This indicates that by designing the metasurface, it is possible to generate independently modulated multi-mode OAM vortex beams. This capability can fulfill the need for independent phase control in multiple channels within a communication system, thereby enhancing communication capacity and efficiency.

To achieve better transmissive metasurface characteristics, multifunctional superlenses can be used to generate dynamic multi-OAM vortex beams. However, such superlenses must not only meet the phase variations required for beam generation but also provide different polarizations. In 2021, Gu et al.²³⁸ proposed a composite metasurface that integrates a metasurface with a superlens to generate dynamic multi-mode OAM vortex beams. However, this method still faces challenges such as device complexity and limited beam quality.

In 2023, Li et al.²³⁹ introduced a multi-layer programmable metasurface with a single feed source. Combining mode and spatial division multiplexing, they designed a prototype of a transmissive digital coding metasurface (TDC-MS). By altering the geometric shapes of orthogonal dipoles, they achieved polarization-

dependent 3-bit phase responses and encoded phase sequences in both x and y directions. This design enables the simultaneous generation of four OAM beams with topological charges of -2 and $+1$ in different directions, allowing for precise control of OAM beams with two types of topological charges in four distinct directions.

In 2023, Li et al. proposed a broadband dual-polarized reflective metasurface²⁴⁰. The unit structure of this metasurface was designed based on geometric symmetry, enabling it to exhibit identical electromagnetic responses to orthogonally polarized waves, thereby achieving dual-polarization characteristics. The proposed approach effectively addressed the issue of high crosstalk in the combination of OAM multiplexing and polarization multiplexing, reducing the crosstalk between different OAM modes and polarizations to levels below -16 dB and -21 dB, respectively. Within the broadband range of 90–110 GHz, the metasurface was able to simultaneously generate two coaxially propagating OAM beams, with each polarization state corresponding to a different OAM mode. To demonstrate the application of the metasurface in wireless communications, the authors built a terahertz wireless communication system that multiplexed four independent OAM beams, each carrying a 6 Gbaud QPSK signal, successfully achieving a total transmission rate of 48 Gbit/s with a BER below 3.8×10^{-3} .

In 2024, Li et al. introduced a novel broadband Huygens transmissive metasurface capable of manipulating non-diffracting OAM beams at a frequency of 0.1 THz²⁴¹. By flexibly controlling the phase, this metasurface combined hyperbolic phase, OAM phase, and conical lens phase to multiplex two high-order Bessel beams. It achieved the generation of high-purity non-diffracting OAM beams over a broadband range of 20 GHz. Based on this design, the team conducted the first experimental demonstration of a 112 Gbit/s photonic terahertz wireless communication system using two non-diffracting OAM beams, with each channel carrying a 14 Gbaud 16QAM signal. A comparative study of the communication performance between high-order Bessel beams and conventional OAM beams revealed that the more stable field distribution of high-order Bessel beams was beneficial for improving the SNR.

In 2024, Yang et al. generated dual perfect vector vortex beams by integrating a Dammann vortex grating into an all-dielectric metasurface²⁴². Although all-dielectric metasurfaces exhibit lower absorption loss at high frequencies compared to metallic metasurfaces, the emer-

gence of active metasurfaces has introduced greater flexibility in generating vector beams, additionally enabling spatiotemporal modulation.

In 2024, Huang et al. designed a broadband dual-band cross-reflection metasurface with 2-bit phase discretization by optimizing the resonant field and current distribution of the metasurface²⁴³. This design achieved 2-bit phase modulation across a wide frequency range. The metasurface was capable of independently controlling the transmission and reflection properties of electromagnetic waves in two frequency bands, successfully overcoming the challenge of simultaneously achieving multi-band functionality and high efficiency in conventional designs.

In 2024, Zhang et al. proposed an active inductive magnetic Huygens metasurface (AIMHM) based on the principles of Huygens metasurface design and integrated with active devices²⁴⁴. By designing an inductive magnetic Huygens unit, the authors realized efficient electromagnetic wave transmission. They further introduced two simplified wiring schemes to reduce the impact of complex wiring on the unit's resonance characteristics, effectively addressing two major challenges in the design of transmissive active OAM metasurfaces. By adjusting the voltage of varactor diodes on each metasurface unit, eight dynamic phase states could be achieved. Initially, the metasurface generated OAM beams with different topological charges for OAM multiplexing communication. Subsequently, it produced OAM beams with arbitrary topological charge harmonic spin, facilitating research on harmonic vortex manipulation. Finally, the authors successfully generated $l = \pm 1$ order vortex beams at a frequency of 5.96 GHz, demonstrating the ability of transmissive active coding metasurfaces to generate vortex beams and paving the way for the development of transmissive vortex beam communication.

In 2024, professor Huang YD's team at Tsinghua University proposed a cascaded architecture that utilizes N -layer polarization-dependent metasurfaces combined with polarization controllers²⁴⁵. This approach increased the number of tunable channels of polarization-dependent metasurfaces from 2 to $2N$, enabling dynamic beam steering, dynamically tunable-order vortex beam generation, and zoom metalenses. Experimentally, the team demonstrated an eight-channel tunable-order vortex beam and eight-channel dynamic beam steering by cascading three metasurfaces with liquid crystal polarization retarders. To further enhance the number of

channels, the researchers cascaded N polarization-dependent metasurfaces and added a polarization controller before each metasurface, allowing the input light to switch between two orthogonal polarization states. As a result, the polarization states in the entire cascaded structure exhibited $2N$ combinations, corresponding to $2N$ equivalent wavefront manipulation templates. Based on different metasurface cascaded configurations, the topological charge of the vortex beam could be tuned between $l = -3$ to $+4$ or $l = -1$ to -8 , with an efficiency ranging from 31.6% to 33.7% in the former case. The beam-steering direction could be arranged in either an 8×1 one-dimensional array or a 4×2 two-dimensional array, with efficiencies ranging from 15% to 25%.

Conclusion and outlook

Coding metasurfaces, as an emerging technology in wireless communication, demonstrate significant potential and application prospects in channel estimation, beamforming, coding design, and transmitter architecture. Through in-depth research into the applications of coding metasurfaces, their multiple advantages in wireless communication systems become evident, providing a clearer understanding of future development directions^{246–275}.

This paper provides a comprehensive review of microwave communication research based on coding metasurfaces, covering various aspects from fundamental theories to practical applications. By analyzing key technologies such as channel estimation, channel modeling, and beamforming, it highlights the advantages and challenges of wireless relay technologies based on digital metasurfaces. Additionally, it explores different information modulation methods for coding metasurfaces, revealing their potential to enhance communication system performance.

The paper also emphasizes transmitter architectures and new wireless communication systems based on coding metasurfaces, showcasing their application prospects for efficient and flexible communication. Furthermore, it discusses the future development directions of metasurface-based vortex light field communication, identifying research hotspots and potential applications in this emerging field^{276–288}.

In practical applications, coding metasurfaces not only enhance communication system coverage and transmission rates but also facilitate multi-user communication, resource allocation, and optimization algorithms.

They can also improve communication security and user privacy through encryption and authentication technologies, offering more secure and reliable communication services. As technology advances and application scenarios expand, coding metasurfaces are expected to play an increasingly important role in wireless communication. Future research may further explore performance optimization and application innovation in specific environments, such as mobile communication and targeted deployments.

In recent years, the application of artificial intelligence (AI) in wireless communications has made significant progress. AI-powered intelligent metasurfaces based on deep learning and reinforcement learning can dynamically adjust the electromagnetic response of metasurface elements through adaptive learning, thereby optimizing the performance of wireless communication systems. AI-driven intelligent coded metasurfaces can regulate channel states in real-time within complex electromagnetic environments, enhancing beamforming, interference suppression, and energy efficiency. Optimizing coded metasurfaces using DNN can significantly reduce computational complexity and improve the adaptability of communication systems. The integration of AI and coded metasurfaces is expected to become a key trend in wireless communication technology development, driving the advancement of intelligent wireless environments.

Beyond classical wireless communication, coded metasurfaces also demonstrate potential in quantum communication. Quantum communication relies on the precise control of quantum states, such as OAM and quantum entanglement, while coded metasurfaces can accurately modulate the wavefront of photons. Programmable photonic control based on coded metasurfaces can enhance the stability of quantum channels and improve the transmission efficiency of quantum bits.

Overall, communication technologies based on coded metasurfaces provide new insights and solutions for the development of future wireless communication systems. As AI-driven intelligent metasurfaces and quantum communication applications continue to evolve, coded metasurfaces will play an increasingly central role in next-generation wireless communication systems. However, several challenges remain to be addressed, including advancements in fabrication techniques, improvements in system stability, and enhanced environmental adaptability for practical applications.

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Acknowledgements

This work was supported in part by National Natural Science Foundation of China (U24A20307 and 62175224); in part by the science and technology innovation leading talent project of special support plan for high-level talents in Zhejiang Province (2021R52032); in part by the China Jiliang University Basic Research Expenses; Zhejiang University Students Science and Technology Innovation Activity Plan - New Talent Plan(2024R409C054); in part by the Natural Science Foundation of Zhejiang Province under Grant (ZCLZ25F0502).

Competing interests

The authors declare no competing financial interests.