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Original Article

Study the Cognitively Adaptive Photonic Metasurfaces for Self-Evolving Light–Matter Interaction

Dr. Upendra Kumar[1], Dr. Deepak Kumar[2]
[1]Head, Department of Physics, G. D. College, Begusarai
[2]Assistant Prof. (Sr. Scale), University Dept. of Physics, L. N. Mithila University, Darbhanga

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Correspondence Address:
Dr. Deepak Kumar
Assistant Prof. (Sr. Scale), University Dept. of Physics, L. N. Mithila University, Darbhanga
Email: deepakphy@lnmu.ac.in

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Abstract

Photonic Metasurfaces have emerged as powerful platforms for sculpting electromagnetic waves at deeply subwavelength dimensions, enabling compact control over phase, amplitude, polarization, and wavefront topology. Despite these advances, most reported metasurfaces operate as static or externally driven devices, limiting their capacity to respond autonomously to fluctuating optical environments. In this paper, we explore a new conceptual paradigm, Cognitively Adaptive Photonic Metasurfaces (CAPMs), in which learning, memory, and adaptive behavior arise intrinsically from light–matter interaction. CAPMs are composed of resonant meta-atoms endowed with internal state variables that evolve in response to optical excitation, allowing the metasurface to modify its functionality based on illumination history. By integrating nonlinear optical responses, phase-change dynamics, and localized feedback, we develop a theoretical framework describing the self-evolution of optical states under spatiotemporally varying fields. This abstract reveals how memory formation, adaptive optimization, and predictive behavior can naturally emerge in metasurface architectures. The proposed concept opens a pathway toward intelligent photonic matter with potential applications in self-optimizing optical communication, adaptive imaging, neuromorphic photonics, and autonomous sensing systems.

Keywords: *Adaptive photonics, intelligent metasurfaces, nonlinear optics, Optical memory, Neuromorphic photonics, Self-learning systems*

Introduction

Photonics has undergone a profound transformation over the past two decades, driven largely by the emergence of metasurfaces, ultrathin, planar arrangements of subwavelength resonators engineered to manipulate electromagnetic waves with extraordinary precision [1]. By tailoring the geometry, orientation, and material composition of individual meta-atoms, metasurfaces enable precise control over fundamental optical properties, including phase, amplitude, polarization, and wavefront shaping. This capability has led to groundbreaking applications, including flat and ultrathin lenses, high-efficiency holography, compact polarization converters, vortex beam generators, and dynamic beam steering devices [2]. Compared to conventional bulky optical components, metasurfaces offer significant advantages in terms of compactness, integrability, and multifunctionality, making them highly attractive for next-generation photonic systems [3].

Despite these remarkable achievements, the majority of metasurface platforms developed to date remain intrinsically static. Their optical response is typically fixed at the design stage and optimized for a specific operating condition or wavelength range. Although recent efforts have introduced tunable and reconfigurable metasurfaces using external stimuli, such as electrical gating, thermal modulation, mechanical deformation, or optical pumping, these approaches generally rely on predefined control schemes [4]. In such systems, adaptability is imposed externally through electronic circuits or control algorithms, rather than emerging intrinsically from the photonic structure itself. Current metasurfaces lack autonomy and are unable to respond intelligently to unpredictable or continuously evolving optical environments.

In stark contrast, natural light–matter interaction in biological systems is inherently dynamic and adaptive. Biological photoreceptors, for instance, adjust their sensitivity depending on illumination conditions, enabling vision across a wide range of light intensities [5].

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Adaptive camouflage systems in nature dynamically modify optical appearance in response to environmental cues, while neural vision systems continuously learn from visual stimuli, refining perception through experience and memory. These systems do not rely on centralized external controllers; instead, intelligence and adaptability emerge from local interactions, feedback mechanisms, and internal state evolution. Such characteristics are largely absent in conventional photonic devices, highlighting a fundamental gap between artificial optical systems and their natural counterparts [6].

Bridging this gap requires a paradigm shift in photonic design, from static or externally controlled devices toward systems that possess intrinsic adaptability, memory, and learning capability. Recent advances in nonlinear optical materials, phase-change compounds, and neuromorphic computing provide compelling evidence that intelligence can be embedded directly into physical matter. Materials exhibiting optical nonlinearity, hysteresis, or nonvolatile phase transitions naturally possess internal state variables that evolve in response to optical excitation [7,8]. When combined with subwavelength resonant structures, these materials open the possibility of photonic systems that can sense, process, and store information entirely in the optical domain.

The programmable or tunable metasurfaces that merely execute externally defined commands, CAPMs, are envisioned as self-evolving optical interfaces. Their response is governed by internal state variables that change through local feedback, learning dynamics, and interaction history. In this paradigm, the metasurface does not simply manipulate light—it learns from it. Repeated or structured illumination can lead to the emergence of stable optical states, effectively enabling memory formation and adaptive optimization of functionality [9].

The objective of this paper is to establish a theoretical and conceptual foundation for CAPMs. We focus on the physical principles underlying self-evolving optical responses, the mechanisms through which learning and memory can arise in metasurface architectures, and the broader implications of embedding cognitive behavior into photonic matter[10,11]. By doing so, this work aims to open a new research direction at the intersection of photonics, adaptive materials, and intelligent systems, paving the way toward autonomous, self-learning optical technologies.[12]

Conceptual Framework of Cognitively Adaptive Metasurfaces:

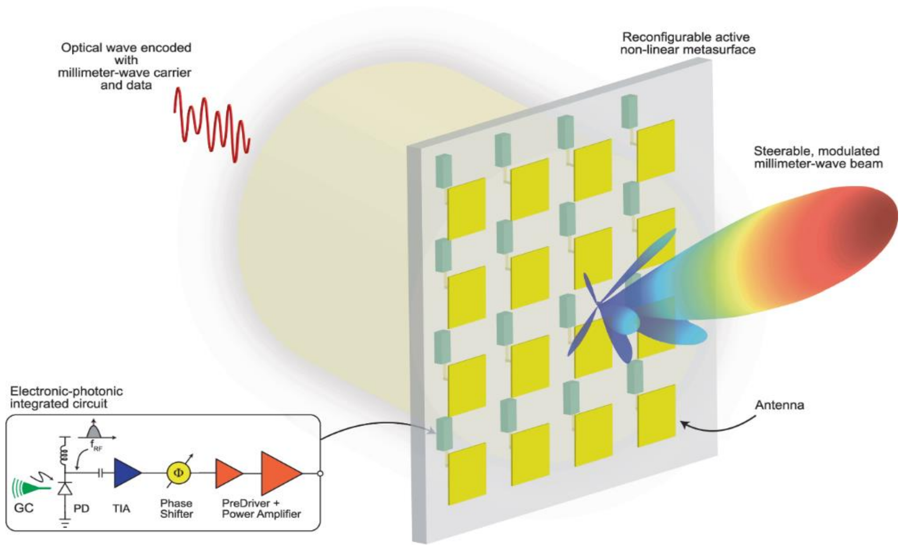

Figure 1 illustrates that electronically driven, reconfigurable nonlinear metasurfaces can directly convert and process optically encoded information into steerable millimeter-wave radiation, enabling seamless optical–RF (mm-wave) transduction and beam control [13].

The concept of *Cognitively Adaptive Photonic Metasurfaces (CAPMs)* represents a fundamental departure from conventional metasurfaces. Traditional metasurfaces are typically engineered to perform a predetermined optical function, such as focusing, beam deflection, or polarization conversion, under fixed operating conditions. Even reconfigurable metasurfaces rely on external control inputs that explicitly dictate the desired response. CAPMs are rooted in the idea that adaptability, learning, and memory should emerge intrinsically from the metasurface itself, without continuous external supervision [14].

At the core of a CAPM lies the notion of a *meta-atom* endowed with an internal state variable. Each subwavelength resonator is not merely a passive scatterer of light but an active optical element capable of sensing the local electromagnetic field and modifying its response accordingly. This internal state may be associated with material properties such as refractive index, absorption coefficient, carrier density, or phase composition, which can evolve in response to optical excitation [15]. The current optical response of the metasurface depends not only on the instantaneous incident field but also on the history of prior illumination, thereby introducing memory into the system.

A defining feature of CAPMs is the presence of local feedback mechanisms. When light interacts with a meta-atom, it induces changes in the internal state through processes such as nonlinear polarization, photo-induced heating, carrier excitation, or phase transitions [16]. These changes, in turn, alter the scattering characteristics of the meta-atom, modifying the local electromagnetic field distribution. This closed-loop interaction between light and matter forms the physical basis for self-adaptation. Over repeated exposure to specific illumination patterns, the metasurface can gradually evolve toward optical states that minimize energy dissipation, enhance coupling efficiency, or optimize a target functionality such as focusing or beam steering [17].

Another element of the conceptual framework is *collective behavior*. Although each meta-atom operates locally, near-field and far-field electromagnetic coupling between neighboring elements enables information to propagate across the metasurface. This interaction allows CAPMs to exhibit emergent global behavior that cannot be inferred from a single unit cell. Analogous to neural networks, where simple neurons collectively give rise to complex cognition, CAPMs leverage spatial coupling to achieve distributed learning and pattern recognition in the optical domain [18].

The learning dynamics in CAPMs can be understood through an analogy with synaptic plasticity in biological neural systems. Just as synaptic strengths evolve based on neural activity, the optical response of each meta-atom evolves based on local field intensity and interaction history. Certain illumination patterns can be "remembered" through stabilized internal states, while others may fade due to relaxation or competing stimuli [19]. This balance between adaptability and stability is crucial for preventing uncontrolled drift while enabling meaningful learning. The concept of Cognitively Adaptive Metasurfaces envisions photonic structures as active, self-modifying systems rather than static optical components. By embedding feedback, memory, and collective learning directly into the metasurface architecture, CAPMs provide a pathway toward intelligent photonic matter capable of autonomous decision-making, environmental awareness, and long-term adaptation [20].

1. **Fundamental Concept:** A Cognitively Adaptive Photonic Metasurface (CAPM) can be rigorously defined as an artificially structured optical interface composed of subwavelength resonant elements that possess the ability to *sense, remember, learn from, and adapt to* incident electromagnetic fields [21]. Unlike conventional photonic metasurfaces, which are designed to perform a fixed optical function or respond only to externally imposed control signals, CAPMs exhibit autonomous behavior driven by intrinsic physical processes. Their defining feature is the presence of internal state variables that evolve dynamically in response to optical stimuli, allowing the metasurface to modify its functionality over time.

The first defining characteristic of a CAPM is its ability to sense incident electromagnetic fields locally. Each meta-atom acts as a nanoscale sensor, where strong field confinement and resonance enhancement amplify the interaction between light and matter [22]. This local sensing does not require external detectors; instead, the optical field itself directly influences the material state of the resonator through mechanisms such as nonlinear polarization, carrier excitation, or optical heating. As a result, the metasurface inherently perceives variations in intensity, phase, wavelength, and polarization of the incoming light.

Secondly, a CAPM modifies its optical response based on prior illumination history. This history dependence arises from material properties that do not immediately relax to their original state after excitation. For example, hysteretic refractive index changes or partial phase transitions enable the metasurface to respond differently to the same optical stimulus depending on past exposure [23]. Consequently, the optical response becomes path-dependent, a key hallmark of learning behavior in physical systems.

The third core attribute is the ability to retain memory of previous states. Memory in CAPMs is physically encoded in the persistent internal configuration of each meta-atom, such as residual structural phases, trapped charges, or metastable electronic states. This nonvolatile or semi-volatile memory allows the metasurface to store information about prior optical environments, enabling long-term adaptation without continuous energy input [24].

CAPMs evolve autonomously toward optimized optical functionality. Through repeated interaction with light, feedback-driven state evolution, and coupling between neighboring meta-atoms, the metasurface gradually converges toward optical configurations that minimize loss, enhance efficiency, or reinforce frequently encountered illumination patterns. This self-optimization occurs without external supervision, reflecting an emergent form of optical intelligence. The core idea of CAPMs lies in the intimate coupling of resonant nanostructures with materials exhibiting nonlinear, hysteretic, or phase-transition behavior. This coupling transforms metasurfaces from passive optical components into adaptive photonic matter, capable of learning, forming memories, and evolving autonomously.

2. **Distinction from Conventional Metasurfaces**

Feature	Conventional Metasurfaces	CAPMs
Adaptability	Static or externally tuned	Autonomous
Memory	None	Intrinsic
Feedback	External controller	Local optical feedback
Intelligence	Absent	Emergent

Theoretical Model

1. **Optical State Variable**

Each metasurface unit cell is described by an internal state parameter ξi(t)\xi_i(t)ξi(t), representing its optical memory (e.g., refractive index phase, crystallization fraction, carrier density).

The local response function becomes:

$$\Phi_i = \Phi(E_i, \xi_i) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{A}$$

Where E_i is the local electric field.

2. **Learning Dynamics**

The evolution of the internal state is governed by:

$$\frac{d\xi_i}{dt} = \alpha\,|\,Ei\,|^2 - \beta\xi_i + \gamma\nabla^2\xi_i \quad \ldots\ldots\ldots\ldots\ldots\text{B}$$

Where: α controls sensitivity to optical stimulus,β represents relaxation or forgetting and γ accounts for spatial coupling between neighboring cells

This equation mirrors learning and diffusion processes found in neural systems.

3. **Emergent Optical Memory**

Under repeated illumination patterns, stable attractor states emerge:

$\xi_i(t\rightarrow\infty) \rightarrow \xi_i^*$ ……………………………C

Corresponding to learned optical responses such as optimized focusing or beam steering.

4. **Physical Implementation Pathways**

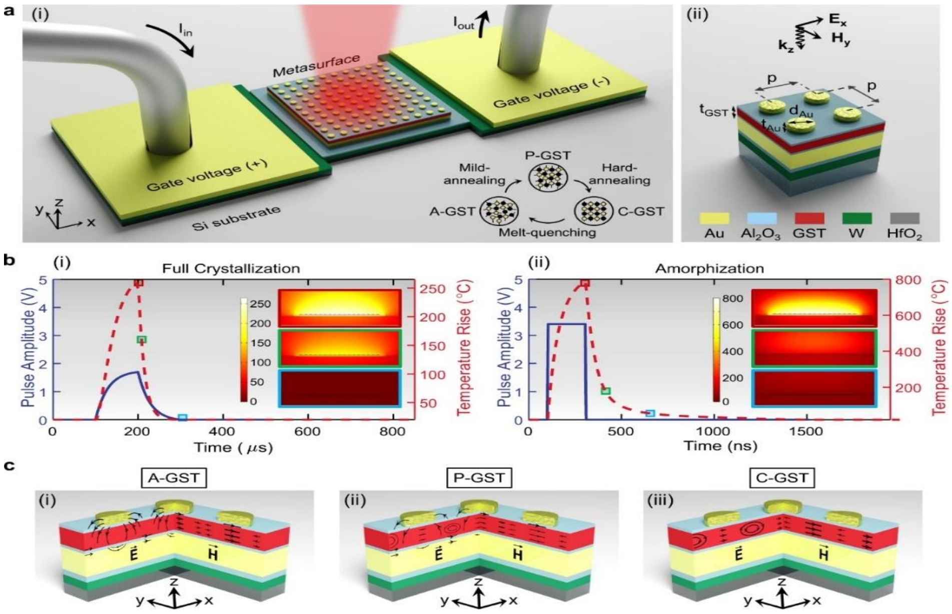

Figure 2. This figure shows that electrically driven phase-change processes enable multilevel, reconfigurable control of light–matter interaction in a photonic metasurface[25]

(a) Device concept and operation

(i) A gate-controlled metasurface integrated on a Si substrate uses electrical pulses to locally tune the phase-change material (GST).

By applying positive/negative gate voltages, the metasurface can be programmed and reprogrammed without altering its physical structure.

(ii) Each meta-atom consists of a Au nanoresonator / Al_2O_3 spacer / GST / W / HfO_2 stack, supporting tailored electromagnetic (E, H) responses under incident light.

(b) Electrical pulse–induced phase transitions

(i) Full crystallization: Longer, moderate-amplitude electrical pulses induce controlled heating, driving GST into the crystalline (C-GST) phase via nucleation and growth.

(ii) Amorphization: Short, high-amplitude pulses cause rapid heating and quenching, freezing GST into the amorphous (A-GST) phase.

The plots correlate pulse amplitude and duration with temperature rise, demonstrating deterministic switching between material states.

(c) Multilevel optical states

(i) A-GST, (ii) partially crystalline GST (P-GST), and (iii) C-GST exhibit distinct electromagnetic field distributions.

So, these states correspond to different effective refractive indices and optical responses, enabling analog (multilevel) tuning rather than binary switching. The figure also demonstrates that electrical programming of GST meta-atoms enables stable, reversible, and multilevel optical reconfiguration, forming the physical basis for adaptive, memory-enabled, and cognitively inspired photonic metasurfaces capable of self-evolving light–matter interaction.

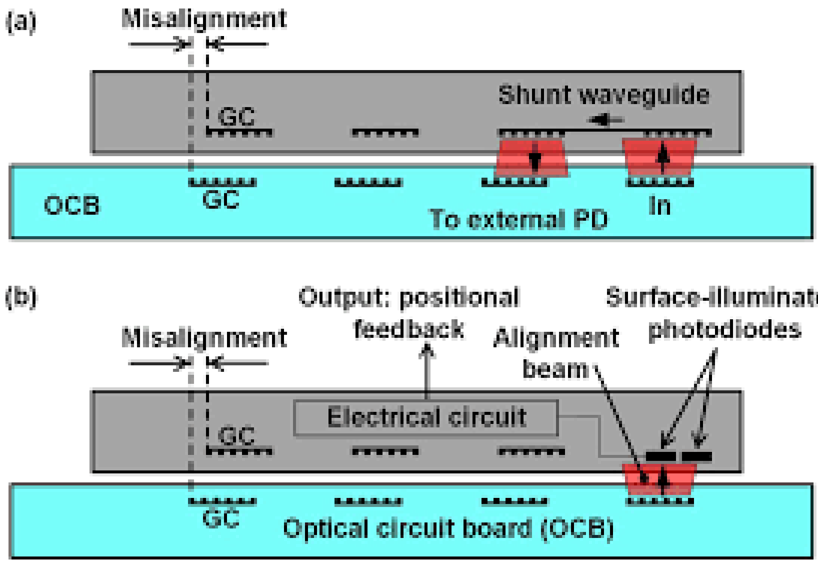

Figure 3. This figure shows that active optical–electrical feedback can automatically detect and correct waveguide misalignment, enabling self-aligned, adaptive photonic interconnects.

The practical realization of Cognitively Adaptive Photonic Metasurfaces (CAPMs) requires the careful integration of subwavelength resonant structures with materials that inherently support state-dependent and history-dependent optical behaviour [26]. One of the most promising implementation pathways involves the use of phase-change materials, which exhibit reversible transitions between distinct structural or electronic phases under optical or thermal excitation. When incorporated into metasurface resonators, these materials enable nonvolatile modulation of refractive index and absorption, providing a physical basis for optical memory and learning.

Another pathway relies on nonlinear optical materials, such as high-index dielectrics or hybrid plasmonic systems, where the local optical response depends strongly on incident field intensity. The strong field confinement within metasurface resonators enhances nonlinear effects, allowing local feedback mechanisms to emerge naturally. Optical heating, carrier generation, and Kerr-type [27] nonlinearities can all contribute to gradual and cumulative modification of the metasurface response under repeated illumination.

From a fabrication perspective, advances in nanolithography, thin-film deposition, and hybrid material integration make it feasible to realize large-area metasurfaces with nanoscale precision. Coupling between neighboring meta-atoms through near-field interactions or thermal diffusion enables collective adaptation across the metasurface. Together, these implementation strategies provide a realistic physical foundation for transforming the conceptual model of CAPMs into experimentally realizable intelligent photonic platforms [28].

1. **Material Systems for Cognitively Adaptive Metasurfaces:**

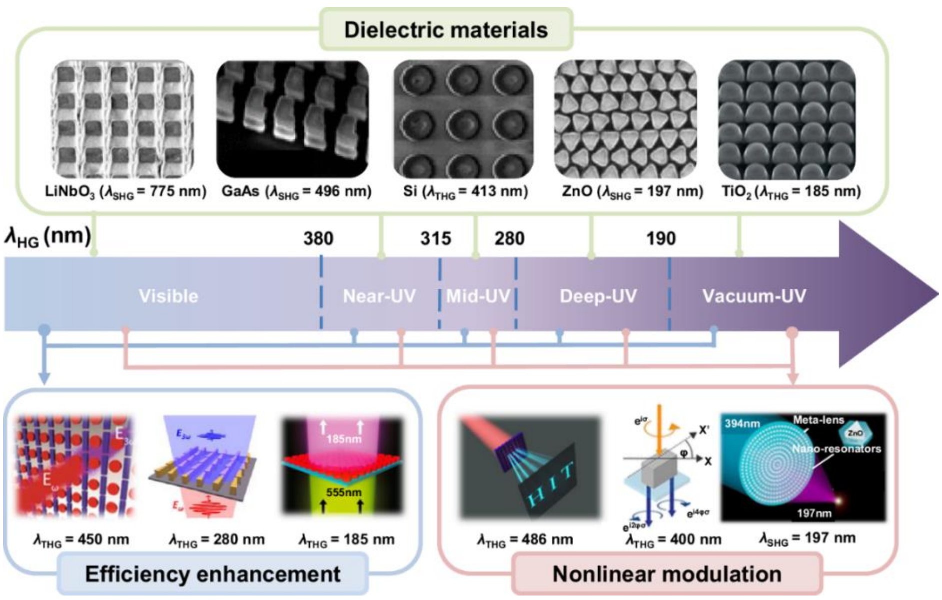

Figure-4. This figure illustrates that dielectric metasurfaces enable highly efficient nonlinear frequency conversion across the visible to ultraviolet spectral ranges through the materials and resonators.

The realization of Cognitively Adaptive Photonic Metasurfaces (CAPMs) critically depends on material platforms that inherently support tunability, memory, and nonlinear light–matter interaction [29]. Three classes of materials are particularly suited for enabling the adaptive and learning behavior required in CAPMs: phase-change materials, nonlinear dielectrics, and hybrid plasmonic–dielectric resonators.

2. **Phase-Change Materials for Nonvolatile Optical Memory**

Phase-change materials (PCMs) are among the most suitable candidates for implementing long-term optical memory in CAPMs. These materials exhibit reversible transitions between distinct structural phases—typically amorphous and crystalline—when stimulated optically or thermally. Each phase possesses markedly different optical constants, allowing persistent modulation of refractive index and absorption. The refractive index contrast can be expressed as:

$$\Delta n = n_{crstalline} - n_{amorphorus} \quad \text{......................D}$$

which often reaches values on the order of $\Delta n \sim 1$, enabling strong optical contrast at the nanoscale. Importantly, once a phase transition is induced, the material remains in that state without continuous energy input, providing *nonvolatile optical memory*. In a metasurface environment, partial phase transitions can encode multiple intermediate states, allowing analog memory and gradual learning rather than binary switching. This property is particularly valuable for implementing history-dependent optical responses and cumulative learning behavior in CAPMs.

3. **Nonlinear Dielectrics for Intensity-Dependent Response**

Nonlinear dielectric materials form the backbone of adaptive photonic functionality by enabling intensity-dependent modulation of optical properties. In such materials, the refractive index depends on the local electric field intensity according to:

$$n(I) = n_0 - n_2 I \quad \text{....................................E}$$

where n_0 is the linear refractive index, n_2 is the nonlinear coefficient, and $I = |E|^2$ is the optical intensity. When integrated into metasurface resonators, strong field confinement dramatically enhances the effective nonlinear interaction, allowing even moderate input intensities to induce significant changes in phase and amplitude.

This nonlinear response enables CAPMs to act as local optical processors, where frequently encountered high-intensity patterns lead to reinforced optical states. Over time, repeated excitation can result in stable self-adapted configurations., Nonlinear dielectrics typically exhibit low optical losses compared to metals, making them suitable for scalable and energy-efficient adaptive metasurfaces[30].

4. **Hybrid Plasmonic–Dielectric Resonators**

Hybrid plasmonic–dielectric platforms combine the extreme field localization of plasmonic structures with the low-loss and tunable properties of dielectric materials. Metallic components concentrate electromagnetic fields into deeply subwavelength volumes, significantly enhancing local optical intensity. Dielectric or active materials placed in these hotspots experience amplified nonlinear or phase-change effects, even under low-power illumination.

The effective field enhancement factor η can be approximated as:

$$\eta = \frac{|E_{local}|^2}{|E_{incident}|^2} \quad \text{...................F}$$

where $\eta \gg 1$ in plasmonic environments. This enhancement enables efficient feedback-driven state evolution, a key requirement for autonomous learning in CAPMs. By carefully balancing plasmonic confinement and dielectric stability, hybrid resonators offer a versatile pathway for achieving adaptive, memory-enabled photonic metasurfaces.

So, the synergy between phase-change materials, nonlinear dielectrics, and hybrid plasmonic–dielectric resonators provides a robust material foundation for CAPMs. These platforms enable memory retention, intensity-dependent learning, and strong light–matter feedback—essential ingredients for transforming metasurfaces into cognitively adaptive photonic systems[31].

5. **Mechanisms of Adaptive Feedback**

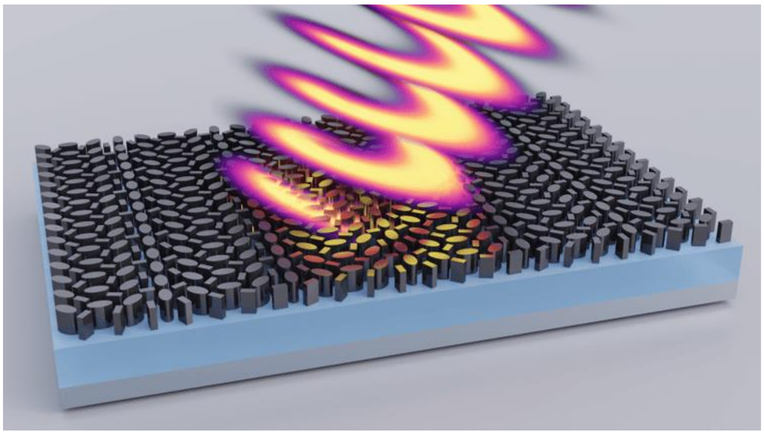

Figure 5. This figure relates to the concept of spatially programmable and adaptive photonic metasu rfaces that enable dynamic wavefront shaping through localized light–matter interaction.

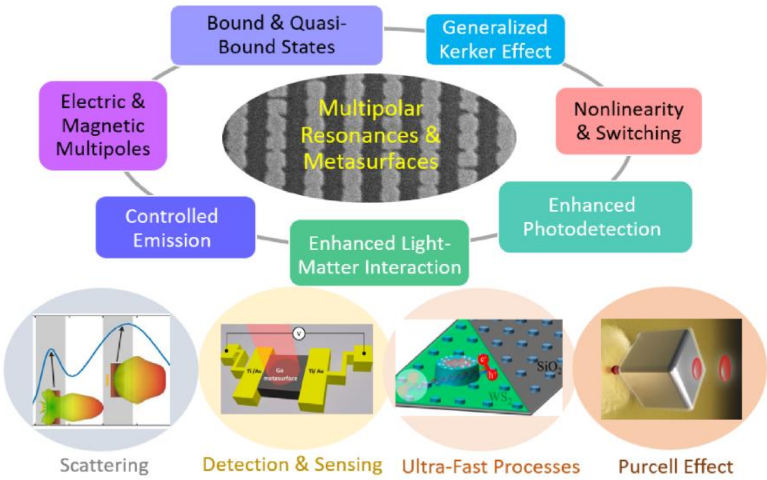

Figure 6. The figure shows that multipolar resonances in dielectric metasurfaces provide a unified physical framework for controlling and enhancing light–matter interaction across multiple functionalities [32,33].

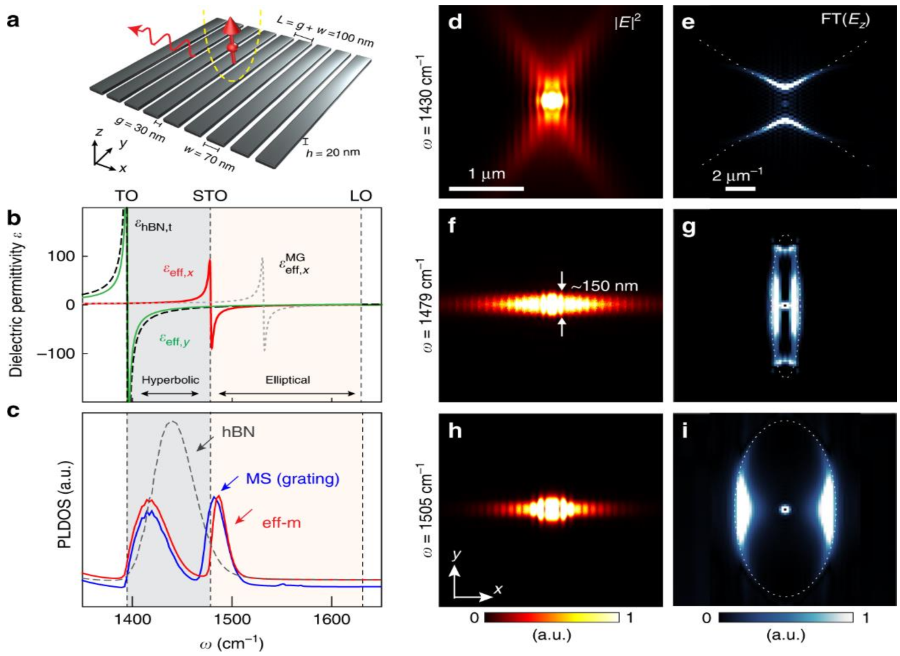

Figure 7. This figure shows that hyperbolic phonon–polaritons (HPPs) can be selectively launched, confined, and dispersion-engineered using anisotropic metasurface gratings, enabling deep-subwavelength control of light–matter interaction.

6. Panel-wise interpretation:

(a) Metasurface geometry: An anisotropic metallic (or dielectric) grating with subwavelength period is placed on a hyperbolic material (e.g., hBN). The grating provides the required momentum matching to couple free-space radiation into high-k polaritonic modes [34].

(b) Effective permittivity and hyperbolic regime: The plot of dielectric permittivity versus frequency shows transverse optical (TO) **and** longitudinal optical (LO) phonon resonances. In the shaded region, the in-plane permittivities have opposite signs, indicating a way to allow tunable polariton propagation. The hyperbolic dispersion regime. metasurface induces anisotropic effective permittivity

$$\boldsymbol{\varepsilon_{eff,x}} \neq \boldsymbol{\varepsilon_{eff,Y}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots G$$

(c) Photonic local density of states (PLDOS): The metasurface (MS grating) strongly enhances **the** local density of optical states compared to bare hBN, confirming efficient polariton excitation and confinement. (d–f) Near-field intensity maps ($|E|^2$). These panels show frequency-dependent polariton propagation**:**

- At ω=1430 cm^{-1}: tightly confined polariton hotspots.
- At ω=1479 cm^{-1} : guided polariton beams with lateral confinement ~150 nm.
- At ω=1505 cm^{-1}: broader propagation as dispersion changes.

7. **Momentum-space (Fourier) images**: The Fourier-transformed fields reveal open hyperbolic isofrequency contours**, a** hallmark of hyperbolic polaritons, demonstrating directional, high-**k** propagation far beyond the free-space light line. Local

feedback mechanisms are the physical backbone that enable Cognitively Adaptive Photonic Metasurfaces (CAPMs) to evolve autonomously without centralized control. Unlike externally driven tuning schemes, feedback in CAPMs is intrinsic and emerges directly from light–matter interaction at the meta-atom level. Three primary mechanisms—optical heating, field-enhanced carrier generation, and near-field coupling—play a decisive role in enabling independent state updates within each resonator[35].

Optical heating arises from the absorption of incident electromagnetic energy within the meta-atom. In resonant nanostructures, strong localization of optical fields can lead to localized temperature increases, even under moderate illumination. This temperature rise can induce refractive index changes, activate phase transitions in phase-change materials, or modify carrier mobility [36]. Importantly, optical heating is cumulative in nature: repeated exposure to specific illumination patterns leads to persistent material modification, thereby encoding memory. Once the optical stimulus is removed, partial relaxation may occur, but residual thermal or structural changes can remain, enabling history-dependent behavior.

Field-enhanced carrier generation constitutes another powerful feedback pathway. In semiconducting or hybrid metasurface materials, intense local electric fields can excite free carriers via multiphoton absorption or interband transitions. The resulting change in carrier density alters the local permittivity according to:

$$\Delta\varepsilon \propto -\frac{Ne^2}{\varepsilon_0 m^* \omega^2} \quad \text{..................H}$$

where N is the carrier density. Since carrier recombination times can vary from picoseconds to much longer timescales depending on material and defect states, the optical response becomes temporally nonlocal, allowing the metasurface to "remember" past illumination. This mechanism supports fast learning dynamics and enables intensity-dependent adaptation.

Near-field coupling between resonators introduces collective feedback across the metasurface. When neighboring meta-atoms interact electromagnetically, a state change in one resonator influences the local field experienced by others[37]. This coupling enables the spatial propagation of learned states, allowing global optical functionalities to emerge from local rules. As a result, CAPMs can exhibit self-organized behavior like neural networks, where learning is distributed rather than centralized.

Potential Applications: The unique ability of CAPMs to sense, learn, and adapt opens transformative opportunities across multiple photonic domains.

1. Autonomous Optical Communication: In free-space optical communication, atmospheric turbulence and alignment fluctuations often degrade signal quality. CAPMs can autonomously self-optimize beam direction, phase distribution, and wavefront shape in response to real-time channel distortion [38]. Through repeated exposure to distorted signals, the metasurface gradually converges toward an optimal transmission state, enabling robust, self-healing optical links without continuous electronic feedback or computation.

2. Intelligent Imaging Systems: CAPMs offer a pathway toward imaging systems that adapt in real time. By learning object features or illumination conditions, such metasurfaces can dynamically adjust focal length, suppress aberrations, or enhance contrast. Unlike conventional adaptive optics, these adjustments occur intrinsically within the optical material, reducing system complexity and latency.

3. Neuromorphic Photonics: The learning dynamics of CAPMs closely resemble synaptic plasticity, where repeated stimuli strengthen or weaken connections. This makes CAPMs highly suitable for neuromorphic photonics, enabling optical neural networks and in-sensor computing. Information processing and learning can thus be performed directly at the optical interface, minimizing data transfer and energy consumption [39].

4. Smart Environmental Sensing: In chemical and biological sensing, environmental conditions are often dynamic and unpredictable. CAPMs can adapt their optical signatures in response to repeated exposure to specific analytes, improving selectivity and sensitivity over time. Such self-evolving sensors could distinguish complex mixtures and adjust detection thresholds autonomously.

Challenges: Despite their promise, several challenges remain. Ensuring the stability of learned optical states is critical, as excessive relaxation or noise could erase stored information. Energy dissipation and thermal effects must be carefully managed to prevent material degradation. Scalability to large-area metasurfaces poses fabrication and uniformity challenges, while integration with existing photonic platforms requires compatibility with standard fabrication and system architectures. Addressing these issues demands interdisciplinary research spanning photonics, materials science, nonlinear dynamics, and device engineering [40].

Future Research Directions: Future investigations may explore quantum-inspired adaptive metasurfaces, where probabilistic learning and coherence effects play a role. Stochastic learning mechanisms could introduce robustness and adaptability in noisy environments. The development of hybrid photonic–electronic cognitive systems may combine optical learning with electronic control for enhanced functionality [41]. Ultimately, realizing experimentally demonstrable prototypes will be a key milestone, transforming CAPMs from a conceptual framework into a practical platform for intelligent photonic technologies.

Conclusion:

This work presents Cognitively Adaptive Photonic Metasurfaces (CAPMs) as a fundamentally new class of intelligent optical matter that integrates sensing, memory, and learning directly into the physical processes of light–matter interaction. Unlike conventional metasurfaces that rely on static designs or externally imposed control, CAPMs evolve autonomously through intrinsic feedback mechanisms, enabling self-learning and history-dependent optical responses. The theoretical framework developed here explores how internal state variables, nonlinear dynamics, and local coupling can give rise to adaptive and self-optimizing photonic functionalities. By bridging photonics with concepts from cognitive and neuromorphic systems, this approach establishes a solid foundation for future experimental realization and paves the way toward truly intelligent, autonomous photonic technologies.

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Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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