Journal of Holography Applications in Physics
Volume 3, Issue 3, Summer 2023, 63-81
© Available online at http://jhap.du.ac.ir
DOI: 10.22128/JHAP.2023.725.1055
Online ISSN: 2783-3518

Journal of Holography Applications in Physics

Review article

Photonic and Plasmonic Encryption Based on Reflection–Transmission Reconfigurable Digital Coding Metasurface in Holographic Images

Ali Farmani[1] . **Hadis Foladi**[1]
[1] School of Electrical and Computer Engineering, Lorestan University, Khoramabad, Iran

Corresponding Author Email: Farmani.a@lu.ac.ir

Received: September 01, 2023; Revised: September 18, 2023; Accepted: September 29, 2023

Abstract. Holography is a powerful technique that enables the manipulation of light waves and has been widely used in imaging, display technologies, and security. Recently, the field of plasmonics has emerged as a promising platform for creating holographic metasurfaces. Plasmonics holographic metasurfaces utilize plasmonic materials and engineered nanostructures to control and redirect light at the nanoscale. In this review, we provide a comprehensive overview of the recent developments in plasmonics holographic metasurfaces, including design principles, fabrication methods, and applications. We discuss different types of plasmonic materials and their properties for holographic metasurfaces, and explore the various approaches for engineering metasurfaces with desired functionalities. Furthermore, we summarize the state-of-the-art fabrication techniques, such as electron beam lithography and nanoimprint lithography, which are commonly employed for the fabrication of plasmonic holographic metasurfaces. Finally, we present the wide range of applications enabled by these metasurfaces, including beam shaping, holographic displays, optical encryption, and biosensing. This review aims to provide a comprehensive understanding of plasmonics holographic metasurfaces and their potential for future advancements in various disciplines.

Keywords: Encryption; Hologram; Metasurface; Photonics; Plasmonics.

---

1 Introduction

Holography, which involves the precise manipulation of light waves, has revolutionized imaging and display technologies. Traditional holography relies on the interference of light waves to produce three-dimensional (3D) images. However, the complex and bulky optical setups required for holographic imaging limit its applicability. The advent of metasurfaces, ultrathin surfaces covered with subwavelength nanostructures, has brought about new opportunities for creating lightweight and compact holographic devices. Metasurfaces can manipulate the amplitude, phase, and polarization of light waves with unprecedented control, allowing for new possibilities in holography. Among various metasurface platforms, plasmonics has emerged as a promising choice due to its ability to confine light at the nanoscale and exhibit strong electromagnetic resonances. Due to the security importance of transferring images and data using the national Internet and network, fast and secure encryption is an important issue [1]. Safe transfer of data in bank systems, social media, the government, security forces, and other systems is very noticeable. Perfect safe encryption has been known since 1882 when a random key as long as a text in World War I was used for top-secret communications. Encryption using telecommunication networks rather than electronic encryption is less complicated with a higher data rate speed [2]. High inherent speed and bandwidth of optical materials and using photonic is an opportunity to manipulate optical signals. Optical systems could be used as a carrier and a connection between logical parameters with other systems, on the other hand, the problem physical systems are executable in optical systems [3]. The data encryption is as asymmetric and asymmetric, in the asymmetric method the same keys are used to encrypt and decrypt and all transmitters can read the encrypted text, so that is not appropriate in multi-user transition. In the asymmetric or multi-level method, optical technology with more security has been used [4]. One of the materials with attention in electronic and photonic applications is fluorescent zero-dimensional silicon nanoparticles (SINPs) that produce visible fluorescents if they are less than 5 nanometers. A using method is Metal-Organic Frames (MOFs) in which SINPs are grown and microwaves are emitted on them. Such material that is wrapped SINP by MOF, shows PH-responsive fluorescence with maximum wavelength and redshift that the pH has increased from 2 to 13 and provides a fluorescence with a lifespan of 2.5 ms, which MOFINPs are used as anti-counterfeiting ink in encryption [5]. In photon materials, nonlinear exists till the local field is large enough and their effective properties are affected and such characteristics can manipulate the electromagnetic fields. Photonic crystal nano-holes are used due to having a nonlinear response in a strong light confinement field [6].

Photonic crystals are used in encryption to save light and recently Colloidal Photonic Crystals (PHCs) have been considered in sensors and anti-counterfeiters [7]. In traditional methods, changing the refractive index and the parameters of the photonic crystals network under magnetic or electrical conditions had been measured or investigated. In nature, many examples of microstructures such as peacock tails, chameleons, butterflies, pearls, etc. existed [8].

Materials such as silk and polymer have been used for transient photonics, which will be unstable if the UV illuminates and causes disorder in the device's life [9]. The electric field directions of a sunbeam differ from the other one, this indicates that the sunbeam polarization is random, but such a beam can be reflected in one direction by a polarizer. The light properties are amplitude, phase, frequency, and polarization, which are used to process and save data. Meta-surfaces have a very thin heterogeneous medium with a flat cross-section and a wavelength structure and are in all frequencies. Compressed, versatility, and nonlinear processes in meta-surfaces and meta-atoms have caused been used in fields such as image encryption and holography. There is a new degree of freedom (polarization) in meta-surfaces [10, 11]. In a single strip element in meta-surfaces, some operations of perception and multiple degrees of free light are modulated more than in bulk optical systems. In meta-surfaces, 3D holographic images are obtained due to modulate the light amplitude and phase simultaneously. In monitoring devices combining holographic colors, when a white light radiates, a fully colored image and when a laser radiates, the encrypted holographic image is displayed [12]. One of the key advantages of holographic metasurfaces is their ability to manipulate different wavelengths of light simultaneously, enabling multispectral imaging and other advanced optical applications. Additionally, their flexibility and compatibility with various substrates make them suitable for integration into a wide range of devices, from smartphones to wearable devices. Here, holographic metasurfaces offer a promising platform for the development of compact, lightweight, and high-performance optical devices with various applications in the fields of optics, photonics, and beyond.

2 Meta-surfaces holography

In meta-surface holography, the resolution of images is better, multi-diffraction is eliminated, and the phase change material (PCM) is reversible and reset. When an external stimulant like heat or a laser beam is applied to them, properties such as their dielectric constant will be changed. Very changes in the amplitude and phase of passing light in amorph crystals with PCM are created. In dual holographic encryption by a single meta-surface, a layer as interlayer "GST", which is between the crystal and amorph states, is put on the glass substrate and encryption is based on a hybrid meta-surface (Fig.1).

When external heat is applied, based on the "A" or "C" state in GST, in the Fourier screen the holographic image of "basketball" or the word "NC" is displayed. In a dual hologram, two independent-phase holograms with the same pixels and GS algorithm are generated and encoded in GST. When the GST phase changes, a meta-surface is used in an independent hologram [13] (Fig.1).

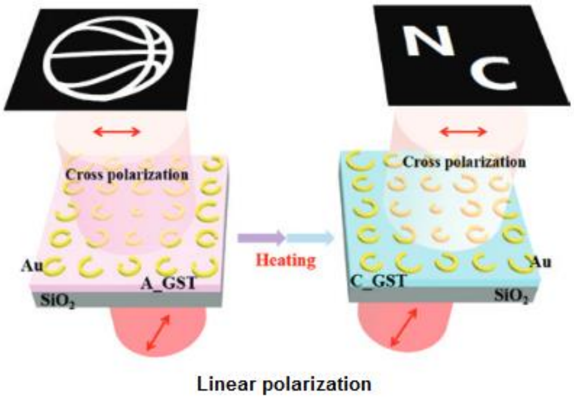

Fig1. double holographic encryption schematic based on hybrid metasurface under amorphous and crystalline states [13]

When the waves are manipulated in various physical dimensions, data can be encrypted with high security. In the multi-wavelength encryption process of an image, some images are decomposed and are encrypted to a single metasurface which has multiple resonance units, that based on the emitted wavelength, show different responses, or both methods are combined [14].

In 1948 one of the most remarkable imaging techniques as holography was invented by Dennis Gabor. This technique enables reconstruction and recording of the information in the images. By developing optoelectronics and computer science, numerical calculations can be used for designing holograms instead of interferometric recording in conventional techniques. Previous methods suffer from poor image re-construction efficiencies and bulky profiles which arise from the inevitable loss. Recently substantial efforts have been made to construct easy to process, more efficient, easy to interrogate and more functional holograms from the spectrum of microwave to terahertz. Surprisingly meta surface material has been found as a good candidate for versatile applications in focusing elements, polarizations optic, holography, vortex beam generation and quantum optics. Hence metasurface materials gained great attention due to their unprecedented flexibility in the manipulation of amplitude, polarization, shape of the local electromagnetic fields and phase with less energy dissipation.

For instance, including color operation, meta surface can either be nonlinear material features of the individual configuration can be used to generate various colored images or subdivided into RGB regions to produce colored images which is an attractive application for the human eye. Furthermore, optics and physics research communities used metamaterials in different modern applications including: antenna engineering, wavefront shaping, absorbing meta devices, intelligent imaging, and Bessel beam generation owing to their exceptional abilities. This state-of-the-art architecture encourages researchers to stimulate meta-holograpgy which improves information encryption and image encoding technology. Regarding the importance of information security, a wide variety of developed decryption/encryption techniques have been reported. Traditional encryption techniques depend on energy requirements, nonlinear optics and implying high intensity. But this novel technology has illustrated excellent potential in information security. As an example, ultrathin nonlinear plasmonic metasurfaces were reported to encrypt images. Another study for high-security encryption proposed orbital angular momentum holography. Additionally, smart multiplexing involving a pair of orthogonal linear polarization states or photon-spin channels is desirable for increasing the capacity of information storage/display and enhancing the metasurface hologram encryption security. For example, meta holograms can be decorated by altering the wavelength or polarization of the incident wave light to generate various images. In previous studies a wide range of dynamic metasurfaces cannot realize THz spectrum information which includes different benefits over conventional imaging wavelength. To overcome this challenge graphene-based meta-atomic was introduced to develop the dynamic meta-holography to the spectrum of THz. Graphene is a hexagonal structure of mono atomic carbon atoms and the thickness of the structure is only the size of one carbon atom. Through chemical doping or external biasing, the electrical conductivity of the surface can be controllable for different functionalities. On the ground that graphene has excellent features, researchers proposed a good architecture for multitasking, re-writable, multichannel information encryption and implementing compact metasurface-based encryption techniques. Consequently, they presented computer-generated meta hologram in which two orthogonal polarized channels act in real time and independently. Remarkable different information with low cross-talk at the region of THz can be achieved. The re-writable characteristic of this structure resulted from voltages biasing control which was applied for each graphene-based pixel and resulted in developing a secure communication protocol and re written information with high contrast, without any polarization rotation and acceptable frequency bandwidth.

Furthermore, the optical media surface demonstrated good ability in light shaping applications. One another example is metaholograms based on photon sieves. Photon sieves is included metal film with nanoholes which are broadband and polarization independent. A group of scientists has explored the operation of a modified aperiodic photon sieve hologram which combined with a geometric phase hologram at red and green wavelengths. In spite of the classical photon sieves, two various aperture kinds, a rectangular and a square one, in an aperiodic arrangement which filled with anisotropic silicon nanoantennas were chosen. Silicon nanoantennas placed in a gold film which provide an excellent platform to not only transmit the desired light and block the light between the nanoapertures but also custom-tailored transmission can be achieved. In this technique, adjusting two apertures leads to encode two distinct amplitude holograms through the nanoantennas dimension. Additionally, in rectangular shape by using the Pancharatnam-Berry (PB) conception phase, the third hologram phase can be encoded. Thus, this device is flexible for applications in switchable holographic displays and provides a wavelength selective operation at multiple wavelengths. It can be concluded metasurface holography surprisingly enhances the resolution of holographic imaging, enlarges the view field, and eliminates multiple diffraction orders. Metasurface brought about enormous change in different applications because of its merits of miniaturization features, planar and subwavelength.

3 Holograms using metasurface

Computational holograms have been expanded by introducing computer holograms since 1966. Holograms can reconstruct virtual objects. Metasurface holograms have a high density due to their sub-wavelength dimensions. Higher-order diffraction orders are eliminated in them, then a higher quality image will be produced [15]. In usual phase holography, phase modulation in wavelength scale is propagated through unit cells and is obtained with different height or refractive indices. Metasurface holography depends on phase discontinuity space changes of a single array containing sub-wavelength antennas. Geometric metasurface holography is caused by the control antenna plate directions [16]. Light would be modulated by degrees of freedom like amplitude, phase, polarization mode, and orbital angular momentum (OAM) [17]. To increase telecommunication bandwidth and improve the security of quantum entanglement and hologram capacity, the OAM multiplexing can be used [18]. OAM modes are carried by vortex beam and are shown by helical phase coefficients and donut-shaped distributions [19].

4 Limitations and challenges in plasmonic holographic metasurface

1. Fabrication complexity: Plasmonic holographic metasurfaces require precise fabrication techniques at the nanoscale to create the desired structures. These techniques can be challenging, time-consuming, and expensive.

2. Limited wavelength range: Plasmonic holographic metasurfaces are often designed to operate in a specific wavelength range. They may not be suitable for other wavelengths, limiting their versatility and applicability.

3. Losses: Plasmonic materials inherently suffer from energy losses due to absorption and scattering. These losses can reduce the efficiency and performance of holographic metasurfaces.

4. Polarization sensitivity: Plasmonic structures are highly sensitive to the polarization of incident light. They may have different responses for different polarization states, which can complicate the design and implementation of holographic metasurfaces.

5. Limited phase control: Holographic metasurfaces rely on precise control over the phase of incident light to create desired optical effects. However, achieving accurate and efficient phase control can be challenging, especially for broadband operations.

6. Angular dependence: The performance of plasmonic holographic metasurfaces can be highly dependent on the incident angle of light. This limits their effectiveness over a wide range of viewing angles.

7. Thermal effects: Plasmonic structures can generate heat when exposed to intense optical fields, leading to thermal effects that can degrade their performance over time.

8. Scalability: Scaling up plasmonic holographic metasurfaces to larger sizes can be difficult, as it requires maintaining the same level of precision and performance across a larger area.

9. Material compatibility: Plasmonic materials often require specific fabrication processes and material choices, which may not be compatible with certain applications or integration with other optical components.

10. Environmental stability: Plasmonic materials can be sensitive to environmental conditions such as humidity, temperature, and exposure to certain gases, which can affect their performance and durability. Ensuring long-term stability and reliability can be a challenge.

5 Digital hologram

In high-capacity holograms, the light physical dimensions such as polarization and wavelength are used. OAM hologram has a helical mode and is used to improve quantum and optical capacities. In this hologram, waves or spiral phases contain information, so OAM characteristics and selectability in image reconstruction must be saved. OAM beams with various helical modes are presented in the Fourier domain to distribute spatial frequency. The larger the spiral modes index, the more distance between the sample points also OAM modes have a sample array and these cause OAM-dependent digital holograms [20].

6 Encryption using plasmonic methods

To design efficient systems in the security field, plasmonic has presented many ways [21]. Nanophotonic structures are used in plasmonic-based optical sensors with high operation. In LSPR or SSP plasmonic-based sensors, the nanoscale of the electric field causes high sensitivity to change around the dielectric environment and such sensors are label-free and real-time [22]. Polarization-mode-based optical methods have high security, in which a polarization "key" as the writing of plasmonic gold nanotubes is required to visualize the main information of encryption. Local field and dispersion are developed by stimulating SPR in nanotubes [23]. Plasmonic properties can be controlled dynamically. In anisotropic plasmonic structures such as gold nanotubes and nanoplates, the redshift is happening for plasmonic excitation peak value to infrared or near-infrared by adjusting geometric dimensions' rate. This redshift in encryption is used so that is hidden from the human eye. The sensor is not exposed to visible and light pollution [24]. Plasmonic-dynamic metasurface devices are used for encryption, which is obtained by changing the refractive index using phase changing chemical material. In them, the image encryption takes place in the form of grey pictures in the infrared region and is hidden under visible light with coupled plasmonic resonance and polarization modulation. To produce or manipulate multiple colors, the size and geometry of nanostructures must be considered. To control the light, the amplitude and phase must be manipulated, by controlling both of them, high-quality holographic images are obtained [25]. To encryption data using colour coding, lifetime regulation, and phasing excitation light the upconversion nanoparticles (UCNPs) could be used, but they have low internal quantum efficiencies and widely are not used. Their multiple sets have complex compounds [26]. The UCNP diffusion can be adjusted using MIM structures. To adjust UCNP emission properties the noble metal nanostructures with plasmon resonance properties are used.

To match the absorption or diffusion bands of UCNPs with resonance bands, the size or the dimension ratio of plasmonic nanostructures must be changed. The excitation rate or radiation emission in UCNPs can be large. New methods are introduced to encrypt by integrating UCNPs plasmonic nanostructures [26].

By light-matter interaction and eliminating a specific wavelength of a bandwidth (white) light source, passive colors are produced. To show colors, pigments and dies are usually used, which absorb a part of the visible spectrum and reflect others to make colors. Pigments are unstable and toxic, which must solve such problems. Color is produced by photon crystals or multilayer structures; metal nanostructures have absorption and dispersion cross-sections that are proper for this purpose. LSPR-based color filters are considered by limiting the light in sub-wavelength and having high resolution. Metasurface structural color production is due to light-matter interaction. In colors sensitive to polarization, color changes without changing geometry or metamaterial material. Polarization-sensitive colors are applicable in cryptographic devices in which a switch is turned on or off due to light polarization. In active adjustable colors, the polarization modes of white light are drawn in different colors. If the polarization of the emitted light or the nanostructure's longitudinal axis is parallel, the colors are created. Such systems with a freedom degree are made to manipulate plasmon resonance and increase color-based data storage capacity and encrypt with polarization keys [27, 28].

One of the key advantages of holographic metasurfaces (as can be seen in Fig.2) is their ability to manipulate different wavelengths of light simultaneously, enabling multispectral imaging and other advanced optical applications. Additionally, their flexibility and compatibility with various substrates make them suitable for integration into a wide range of devices, from smartphones to wearable devices.

Overall, holographic metasurfaces offer a promising platform for the development of compact, lightweight, and high-performance optical devices with various applications in the fields of optics, photonics, and beyond.

To manipulate light in subwavelength, metal/dielectric nanostructures have been used. In such structures, color data is static with low potential in encryption. Therefore, several designs such as mechanical deformation with liquid-crystal-based optical systems have been presented. Also, by changing the light polarization mode in resonant structures a color changes to another color, but created color images provide only dynamic colors whose information can be changed and have limited security applications. In a work, the encrypted structural color with transition polarization and hydrogenated amorphous silicon nanogratings (NG) have been proposed.

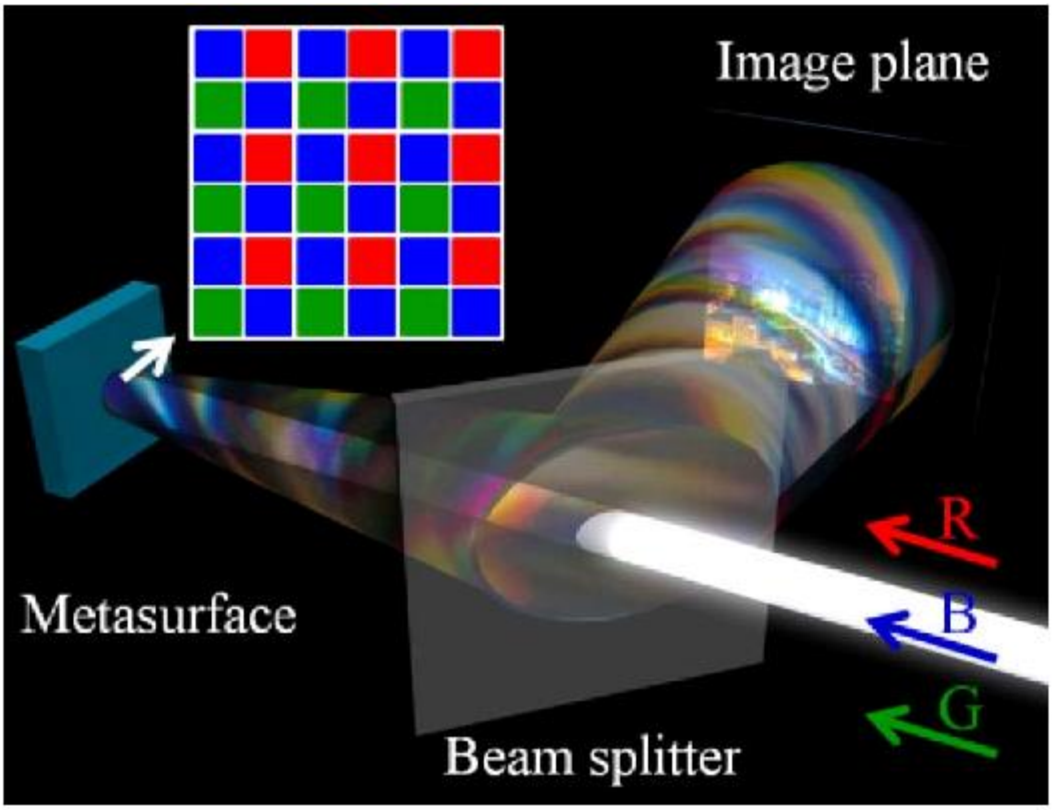

Fig2. Metasurface Holographic image

By irradiating vertically polarized light to the nanogrid, a clear light color is produced. If the polarization mode is parallel to the NG axis, a fixed orange color response is provided. In encryption, color pixels are dependent on polaritons, if the NG numbers in a pixel become less than 4, color pixels are used to encrypt (Fig.3). When the light illumination is as TE polarized, vivid magenta and yellow cross patterns are shown and colors are distinct and if the incident light polarization switches to TM polarization, the three regions I, II and III show an encrypted orange color and the NG information is hidden. Likewise, the color information "NanoNano" is seen by the TE polarized illumination and is invisible by TM polarized illumination, so that, encryption is done [29].

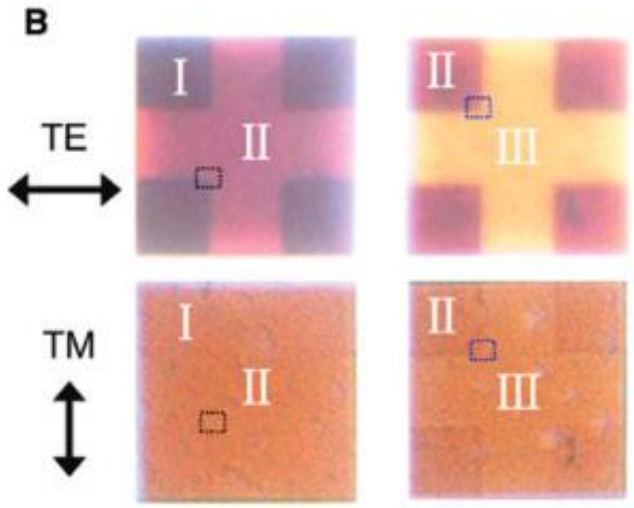

Fig3. The bright-field microscope images of the manufactured microscopic cross images with the TE and TM polarized illuminations. Regions I, II and III represent the NGs [29].

6-1 Fabricating Plasmonic holographic metasurfaces

Plasmonic holographic metasurfaces are engineered surfaces that manipulate light at the nanoscale, allowing for the control and manipulation of light for various applications such as imaging, sensing, and information encoding. Fabricating these metasurfaces requires specific techniques to create the desired nanostructures. Here are some fabrication techniques commonly used for producing plasmonic holographic metasurfaces:

1. Electron Beam Lithography (EBL): This technique uses a focused electron beam to directly write patterns on a resist-coated substrate. It offers high resolution down to the nanometer scale and allows for precise control over feature size, shape, and placement. After patterning, the substrate is typically etched to transfer the pattern into the desired material.

2. Nanoimprint Lithography (NIL): NIL involves pressing a nanostructured mold or template onto the resist-coated substrate to transfer the pattern. It offers high throughput and good pattern quality but is typically limited to relatively large area patterning.

Table1. Introduce various methods and materials, their advantages and disadvantages in encryption applications

Method_Material	Advantages	Disadvantages	Solution
fluorescent zero-dimensional Si nanoparticles (SiNPs)	Low toxicity / excellent degradability [5]		
Photolithography/relief printing		Time-consuming / compact resources [7]	Using inkjet printing [7]
Non-contact inkjet printing	Flexibility adjustment [7]		
Optical material	High intrinsic speed / high bandwidth / high parallelism [3]		
Limited length key (symmetrical)		Low security [2]	Asymmetric method
Asymmetric method	High security [2]	High computational cost / high energy [2]	
Traditional 2D luminescence material		Data overlap/ difficult to distinguish/ low security [4]	Smart luminescence material
Smart luminescence material	High density/ prevent data forgery [4]	limited applications due to its bandwidth and incoherent characteristics [34]	Integration with nanostructures [34]
Dielectric metal nanostructures (plasmonic)	manipulate in subwavelength/ control property dynamically [24]/ size design [25]	remain color data/ limit encryption [29]	hydrogenated amorphous silicon nanogratings (NG)
Tube nanocrystal (materials with nonlinear properties)	Control of high attenuation interactions/ high confinement/ intense focus/ high harmonic production/ full optical modulation [6]		
Photonic crystals or multilayer structures		Limited resolution [28]/ Low spatial resolution/ low quality/ Low refractive index/ Limited absorption or dispersion cross section [27] /change the effective refractive index and hide encryption pattern incompletely and uncertainty [30]	Using metasurfaces/ polarization-sensitive coloring/ metal nanostructures with high adsorption and dispersion cross-section/ LSPR-based color filters
Color filters	high stability/ simple construction/ high potential/ high resolution and storage [27]/ eco-friendly/ high visibility [35]	High thickness / loss material/ non-adjustability [35]	using a layer of resonator/ LSPR-based construction (plasmonic)
Black Phosphorus	Low bandwidth / low energy / high carrier mobility [31]		
1D metasurfaces		Low security [32]	2D metasurfaces
2D metasurfaces (multiple plasmonic antennas)	Miniaturization/ wavelength scalability [36]/ high security [32]		
Optical metasurfaces	High capacity to manipulate light [14]/ ultra-thin heterogeneous area/ phase polarization control/ freedom degree of polarization [10]	ncomplete information session [14]	metasurfaces-based fhase technology
Conventional hologram		Low image resolution/ multiple diffraction [13]	Surface holographymeta
Metasurface holography with ultra-thin nanostructure	Strong light-matter interaction [33]		
Mg metal and MgO dielectric	Eco-friendly [9]		
Fluorescent	Low cost/ high capture capability [4]	Affected by excitation intensity/ colors distribution and concentration/ overlap spectra [4]	
Upconversion nanoparticles (UCNPs)	Exceptional optical properties/ light stability/ narrow diffuse bandwidth/ long life [26]	Low internal quantum efficiency/ complex [26]	Using MIM structures and plasmonic properties
Plasmonic_ Grating	Support multiple plasmonic modes [1]		

3. Nanosphere Lithography: In this technique, a monolayer of self-assembled nanospheres (usually polystyrene or silica) is deposited on a substrate. The nanospheres act as a mask while the substrate is etched. After etching, the nanospheres can be removed, leaving behind a periodic array of holes or pillars that can be used for plasmonic metasurfaces.

4. Focused Ion Beam (FIB) Milling: FIB milling uses a focused ion beam (usually gallium) to directly etch or mill structures on a substrate. It allows for precise and versatile patterning but can be relatively slow and limited in throughput.

5. Chemical Vapor Deposition (CVD): CVD is a technique used to deposit thin films of materials onto a substrate. It can be used to create plasmonic metasurfaces by depositing thin metal films (such as gold or silver) on a patterned substrate.

6. Laser Interference Lithography (LIL): LIL involves overlapping two or more coherent laser beams to induce an interference pattern on a photosensitive substrate. This interference pattern can then be developed to create a periodic structure suitable for plasmonic metasurfaces.

7. Sol-Gel Processing: This technique involves preparing a solution (sol) containing metal precursors and depositing it onto a substrate. The sol is then converted into a solid (gel) through hydrolysis and condensation reactions, forming a thin film. The film can be further processed to create the desired plasmonic structures.

These are just a few examples of fabrication techniques for plasmonic holographic metasurfaces. The choice of technique depends on factors such as pattern complexity, feature size, substrate material, required throughput, and available resources.

By employing holography, plasmonics metasurface holographic encryption provides several advantages over traditional encryption methods:

1. Physical Security: Holograms are difficult to counterfeit or tamper with, making it harder for hackers or unauthorized individuals to access the encrypted data.

2. Visual Information Protection: Holograms can also be used to hide or encrypt sensitive visual information, such as images or text, making it unreadable to unauthenticated users.

3. Enhanced Authentication: Holography can be employed to verify the authenticity of devices or users, ensuring that only authorized individuals can access the encrypted data.

4. Resistant to Attacks: Holographic encryption adds an additional layer of security, making it more difficult for attackers to break through the encryption and gain access to the data.

It is important to note that holographic encryption is a relatively new field and is still in the research phase. However, it shows promise in providing innovative and robust solutions to protect sensitive information in various domains, including data storage, communication systems, and cybersecurity.

A brief comparison of such work and previous is provided in Table.2.

Table2. A comparison between all the presented results and previous works

References	Encryption Structure	Footprint	Resistant to Attacks
[38]	Photonics crystal	>100 μm	low
[39]	Mach-Zehnder interferometer	>1000 μm	good
This work	Plasmonics Metasurface	<50 nm	extra

6-2 Plasmonics Holographic Metasurface: Unlocking the Future of Optical Devices

The field of plasmonics holographic metasurfaces is still in its infancy, holding immense potential for future developments. Ongoing research aims to enhance their efficiency, expand their operational bandwidth, and explore new functionalities. Moreover, combining plasmonics holographic metasurfaces with other emerging technologies, such as artificial intelligence and machine learning, could unlock even more sophisticated applications. The continued advancements in nanofabrication techniques and material engineering are also contributing to the rapid progress in this field, driving the development of new metasurface designs and unprecedented capabilities (as can be seen in Fig. 4).

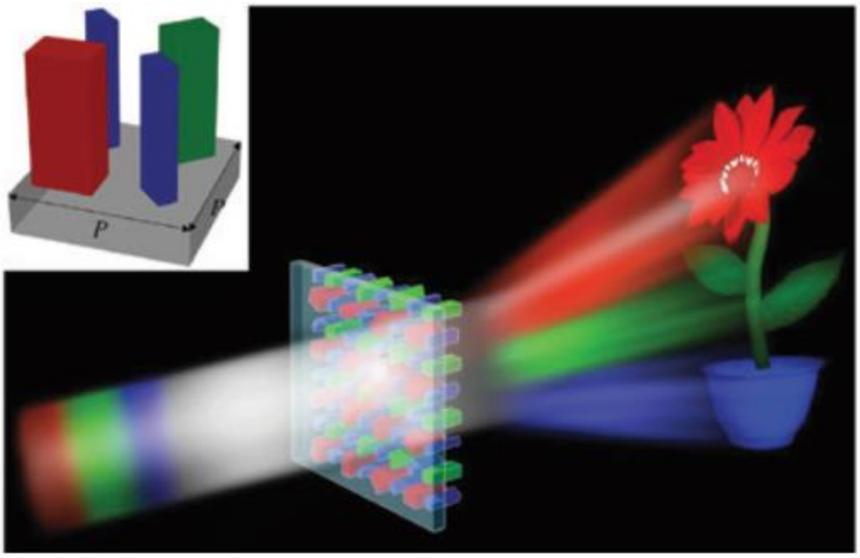

Fig4. New practical applications of plasmonics holographic metasurfaces

7 Conclusions

In conclusion, plasmonics holographic metasurfaces provide a powerful platform for realizing compact and versatile holographic devices. This paper provides a comprehensive investigation of the recent advancements in plasmonics holographic metasurfaces, including design principles, fabrication techniques, and applications in image encryption. The ability to control light at the nanoscale opens up new possibilities for holography in various disciplines. As the field continues to evolve, further advancements in material science, fabrication techniques, and device integration are expected, allowing for even more sophisticated holographic functionalities. The encryption process involves encoding the data into a holographic representation using plasmonic structures. These structures are designed to control the propagation of light and create complex interference patterns that encode the information. This hologram is then combined with an encryption algorithm to secure the data. To decrypt the data, the recipient needs to possess the correct decryption key, which includes the knowledge of how to manipulate the plasmonic hologram. When the hologram is properly manipulated, the encoded information is revealed, providing access to the underlying data.

The advantage of holographic plasmonics encryption lies in its potential for high security and resistance to hacking attempts. The use of plasmonic structures and holography makes it difficult for unauthorized individuals to access and decode the encrypted information without possessing the correct decryption method. Additionally, the integration of encryption algorithms further enhances the security of the system. Holographic plasmonics encryption is an exciting area of research that offers advanced encryption techniques for secure data transmission and storage. It has the potential to revolutionize the field of encryption by providing an additional layer of security based on holography and plasmonics.

Authors' contributions

All authors have the same contribution.

Data Availability

All data included in this paper are available upon request by contact with the contact corresponding author.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical considerations

The authors have diligently addressed ethical concerns, such as informed consent, plagiarism, data fabrication, misconduct, falsification, double publication, redundancy, submission, and other related matters.

Funding

This research did not receive any grant from funding agencies in the public, commercial, or non-profit sectors.

References

[1] Mohamed Abomhara, Omar Zakaria, and Othman O. Khalifa, “An overview of video encryption techniques”, International Journal of Computer Theory and Engineering **2** (1), 103 (2010). DOI: 10.7763/IJCTE.2010.V2.123

[2] Angelos Xomalis, et al., "Cryptography in coherent optical information networks using dissipative metamaterial gates", APL Photonics **4** (4), 046102 (2019). DOI: 10.1063/1.5092216

[3] Hao Jia, et al., "Mode-oriented permutation cipher encryption and passive signal switching based on multiobjective optimized silicon subwavelength metastructures", ACS Photonics **7** (8), 2163-2172 (2020). DOI: 10.1021/acsphotonics.0c00640

[4] Teng Luo, Ting Zhou, and Junle Qu, "Lifetime Division Multiplexing by Multilevel Encryption Algorithm", ACS nano **15** (4), 6257-6265 (2021).

[5] Jinhua Wang, et al., "Multi-modal anti-counterfeiting and encryption enabled through silicon-based materials featuring pH-responsive fluorescence and room-temperature phosphorescence", Nano Research **13** (6), 1614-1619 (2020).

[6] Aivar Abrashuly, and Constantinos Valagiannopoulos, "Photonic memory with nonlinear plasmonic nanotubes", APL Materials **9** (10), 101111 (2021).

[7] Wenyi Li, et al., "Inkjet printing of patterned, multispectral, and biocompatible photonic crystals", Advanced Materials **31** (36), 1901036 (2019).

[8] Hailu Liu, et al., "Functional micro–nano structure with variable colour: applications for anti-counterfeiting", Advances in Polymer Technology **2019**, 6519018 (2019). DOI: 10.1155/2019/6519018

[9] Thomas G. Farinha, et al., "Magnesium for transient photonics", ACS Photonics **6** (2), 272-278 (2018). DOI: 10.1021/acsphotonics.8b01299

[10] Yuttana Intaravanne, and Xianzhong Chen, "Recent advances in optical metasurfaces for polarization detection and engineered polarization profiles", Nanophotonics **9** (5), 1003-1014 (2020). DOI: 10.1515/nanoph-2019-0479

[11] Qinghua Song, et al., "Printing polarization and phase at the optical diffraction limit: Near-and far-field optical encryption", Nanophotonics **10** (1), 697-704 (2021).

[12] Inki Kim, et al., "Pixelated bifunctional metasurface-driven dynamic vectorial holographic color prints for photonic security platform", Nature communications **12** (1), 1-9 (2021). DOI: 10.1038/s41467-021-23814-5

[13] Hongqiang Zhou, et al., "Switchable active phase modulation and holography encryption based on hybrid metasurfaces", Nanophotonics **9** (4), 905-912 (2020).

[14] Zhenfei Li, Malin Premaratne, and Weiren Zhu, "Advanced encryption method realized by secret shared phase encoding scheme using a multi-wavelength metasurface", Nanophotonics **9** (11), 3687-3696 (2020).

[15] Daniel Frese, et al., "Nonlinear bicolor holography using plasmonic metasurfaces", ACS photonics **8** (4), 1013-1019 (2021).

[16] Jianxiong Li, et al., "Addressable metasurfaces for dynamic holography and optical information encryption", Science advances **4** (6), eaar6768 (2018).

[17] Yutao Tang, et al., "Nonlinear vectorial metasurface for optical encryption", Physical Review Applied **12** (2), 024028 (2019).

[18] Haoran Ren, et al., "Orbital-Angular-Momentum-Controlled Hybrid Nanowire Circuit", Nano Letters **21** (14), 6220-6227 (2021).

[19] Hongqiang Zhou, et al., "Polarization-encrypted orbital angular momentum multiplexed metasurface holography", ACS nano **14** (5), 5553-5559 (2020).

[20] Xinyuan Fang, Haoran Ren, and Min Gu, "Orbital angular momentum holography for high-security encryption", Nature Photonics **14** (2), 102-108 (2020).

[21] Michael François, et al., "Generation of encryption keys from plasmonics", PIERS Online **7** (3), 296-300 (2011).

[22] Haoran Zhang, et al., "Biosensing Performance of a Plasmonic-Grating-Based Nanolaser", Progress In Electromagnetics Research **171**, 159-169 (2021).

[23] Min Gu, et al., "Plasmonic keys for ultra-secure information encryption", SPIE Newsroom **19** (2012).

[24] Xiaojing Wang, et al., "Anisotropically shaped magnetic/plasmonic nanocomposites for information encryption and magnetic-field-direction sensing", Research **2018**, 7527825 (2018).

[25] Ting Zhang, and Steve Blair, "Gray level image encoding in plasmonic metasurfaces", Plasmonics **15** (5), 1305-1311 (2020).

[26] Ziwei Feng, et al., "Laser-Splashed Plasmonic Nanocrater for Ratiometric Upconversion Regulation and Encryption", Advanced Optical Materials **7** (19), 1900610 (2019). DOI: 10.1002/adom.201900610

[27] Maowen Song, et al., "Colors with plasmonic nanostructures: A full-spectrum review", Applied physics reviews **6** (4), 041308 (2019).

[28] Chunghwan Jung, et al., “Near-zero reflection of all-dielectric structural coloration enabling polarization-sensitive optical encryption with enhanced switchability”, Nanophotonics **10** (2), 919-926 (2021).

[29] Wenjing Yue, et al., “Polarization-encrypted high-resolution full-color images exploiting hydrogenated amorphous silicon nanogratings”, Nanophotonics **9** (4), 875-884 (2020). DOI: 10.1515/nanoph-2019-0500

[30] Fantao Meng, et al., “Facile fabrication of encryption composite materials with trilayer quasi-amorphous heterostructure”, Science China Materials **64** (4), 909-919 (2021). DOI: 10.1007/s40843-020-1500-9

[31] Hai Lin, et al., “Photonic spin Hall effect of monolayer black phosphorus in the Terahertz region”, Nanophotonics **7** (12), 1929-1937 (2018).

[32] Fengliang Dong, et al., “Information encoding with optical dielectric metasurface via independent multichannels”, Acs Photonics **6** (1), 230-237 (2018).

[33] Ruizhe Zhao, et al., “Multichannel vectorial holographic display and encryption”, Light: Science & Applications **7** (1), 1-9 (2018).

[34] Yinan Zhang, et al., “Extremely polarized and efficient hot electron intraband luminescence from aluminum nanostructures for nonlinear optical encoding”, Laser & Photonics Reviews **15** (1), 2000339 (2021).

[35] Maowen Song, et al., “Color display and encryption with a plasmonic polarizing metamirror”, Nanophotonics **7** (1), 323-331 (2018).

[36] Yinan Zhang, et al., “Full-visible multifunctional aluminium metasurfaces by in situ anisotropic thermoplasmonic laser printing”, Nanoscale Horizons **4** (3), 601-609 (2019). DOI: 10.1039/C9NH00003H

[37] Yu Bi, et al., “Magnetically controllable holographic encryption based on a magneto-optical metasurface”, Optics Express **30** (5), 8366-8375 (2022).

[38] Yong Qi, Lin Chu, Wenbin Niu, Bingtao Tang, Suli Wu, Wei Ma, and Shufen Zhang, “New encryption strategy of photonic crystals with bilayer inverse heterostructure guided from transparency response”, Advanced functional materials **29**, no. 40, 1903743 (2019). DOI: 10.1002/adfm.201903743

[39] Jun Li, Jiaosheng Li, Lina Shen, Yangyang Pan, and Rong Li, “Optical image encryption and hiding based on a modified Mach-Zehnder interferometer”, Optics express **22**, no. 4, 4849-4860 (2014). DOI: 10.1364/OE.22.004849