Insight into plasmonics: resurrection of modern-day science (invited)

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Abstract

Plasmonics is a field of research and technology that focuses on the interaction between light and free electrons in a metal structure called plasmon. The study of plasmonics has gained significant attention in recent years due to its potential for several applications and its ability to manipulate light at nanoscale dimensions. Plasmonics enables the control of light at the nanoscale, far beyond the diffraction limit of conventional optics. This allows for the development of new devices and technologies with enhanced performance and functionality. In this paper, recent advances in plasmonics in medicine, agriculture, agriculture, environmental monitoring, lasers and solar energy harvesting are reviewed. Despite these promising prospects, plasmonic devices must overcome obstacles such as significant energy losses, complicated production processes, and the need for better material characteristics. Plasmonics will continue to advance because of ongoing work in nanotechnology, material science, and engineering, which will make it a more significant field with a wide range of usages in the future. In the end, the advantages and the limitations related to the realization of plasmonic devices in the real world are discussed.

Keywords: plasmonics, surface plasmon polariton, surface plasmon resonance, waveguide, sensors, solar energy harvesting, environmental monitoring; agriculture.

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Introduction

Plasmonics is a field of study that focuses on the interaction between light and metal nanostructures. It has the potential to revolutionize various areas of science and technology [1]. Plasmonic devices can be manufactured on the nanoscale, allowing for compact and integrated systems. These components can be seamlessly integrated with existing semiconductor technology, enabling the development of nanoscale circuits, sensors, and detectors. This miniaturization potential can lead to highly compact and efficient devices for various applications. It's important to note that plasmonics also has its limitations, such as high energy losses and challenges in achieving efficient energy conversion [2]. Therefore, the choice between plasmonics and conventional optics depends on the specific application requirements and the desired trade-offs between different parameters such as device size, speed, integration, and sensitivity.

The field of plasmonics witnessed significant advancements in the early 2000s. Scientists developed various methods for fabricating metallic nanoparticles and nanostructures with accurate shapes and sizes, permitting fine control over their plasmonic properties [3]. This led to the advent of a wide range of plasmonic applications, including sensing, imaging, light manipulation, and energy conversion. There are several noteworthy papers on plasmonic diffractive elements which are suggested to readers [4 – 11]. Since then, plasmonics has continued to evolve rapidly. Researchers have been exploring novel plasmonic materials beyond gold (Au) and silver (Ag), such as aluminium (Al), titanium nitride (AlN), and various semiconductors, aiming to extend the range of plasmonic functionalities and improve performance.

Today, plasmonics has become an interdisciplinary field, drawing expertise from physics, materials science, chemistry, and engineering [12]. It has applications in diverse areas, including telecommunications, data storage, solar energy, biomedical imaging, sensing, and environmental monitoring. Plasmonics offers the possibility of developing ultrafast and compact devices for information processing and computing [13]. Plasmonics can enable the development of nanoscale components for optical communication systems [14, 15]. By confining light to subwavelength dimensions, plasmonic waveguides (hereafter represented as WGs) can transmit data at extremely high speeds. This could lead to faster and more efficient data transfer, revolutionizing telecommunications and networking.

Besides, plasmonic sensors can detect and analyze minute changes in the immediate environment [16]. It enables highly sensitive and selective detection of chemical and biological substances, paving the way for improved medical diagnostics, environmental monitoring, and food safety [17 – 19]. Plasmonics can enhance the efficiency of solar cells by capturing and manipulating light at the nanoscale [20]. Plasmonic nanoparticles can concentrate and trap light, increasing the absorption of photons and improving the overall performance of solar panels. This technology could lead to more cost-effective and efficient solar energy utilization [21].

Plasmonics enables subwavelength imaging, surpassing the diffraction limit of conventional optical microscopy. By using plasmonic nanostructures, researchers can achieve ultra-high-resolution imaging of biological samples, nanomaterials, and other objects at the nanoscale. This can greatly impact various fields, including medicine, biology, and materials science [22].

Plasmonics has the potential to contribute to the field of quantum computing and information processing [23]. Plasmonic nanostructures can be used for the manipulation and control of quantum states, facilitating the development of more efficient quantum devices and communication systems. Continued research and development in this field hold the potential for transformative technological advancements in numerous sectors, leading to faster and more efficient devices, improved sensing capabilities, and novel applications in energy, communication, and medicine [24].

Unlike conventional dielectric WGs, which guide light through total internal reflection, plasmonic WGs operate based on the interaction between light and surface plasmons. This interaction allows for strong field confinement beyond the diffraction limit of light, enabling the manipulation and control of light at subwavelength scales. There are several types of plasmonic WGs, including metal-insulator-metal (MIM) WGs, insulator-metal-insulator (IMI) WGs, V-groove, and hybrid plasmonic WGs [25, 26]. These WGs have different structures and designs but share the common feature of supporting surface plasmons.

A MIM WG is a type of structure that consists of two metal layers separated by an insulating layer. It is used to guide and confine electromagnetic (EM) waves, particularly in the optical frequency range. The structure of a typical MIM WG includes a bottom metal layer, an insulating layer in the middle, and a top metal layer. The insulating layer acts as a dielectric spacer, creating a barrier between the two metal layers. The WG structure is designed in such a way that it supports the propagation of surface plasmon polaritons (SPPs), which are EM waves coupled with electron oscillations at the metal-dielectric interfaces. The metal layers in a MIM WG are usually made of highly conductive materials such as gold (Au), silver (Ag), or aluminium (Al), while the insulating layer can be made of various materials, including silicon dioxide (SiO_2), polymers, or other dielectric materials. The choice of materials depends on the desired operating frequency, loss requirements, and fabrication techniques.

The key advantage of MIM WGs is their ability to confine light to subwavelength dimensions, enabling the manipulation and control of light at the nanoscale [27]. They are particularly useful in applications such as nanophotonics, plasmonics, and integrated optical circuits. MIM WGs can be used for various functions, including signal routing, light confinement, and enhancing light-matter interactions in sensing and spectroscopy applications [15, 18].

However, plasmonic WGs also face challenges. They are typically associated with high propagation losses due to the absorption and scattering of plasmons by the metal. Additionally, strong field confinement can result in a short propagation distance, limiting the overall length of plasmonic WG devices [28]. Researchers are actively exploring new materials, designs, and fabrication techniques to overcome these challenges and optimize the performance of plasmonic WGs [29]. Hybrid plasmonic WGs, which combine plasmonic and dielectric elements, are being investigated to achieve a balance between strong field confinement and low propagation losses. In this review, the advancement of plasmonics in several vital applications is discussed. Fig. 1 presents the areas of research discussed in this paper.

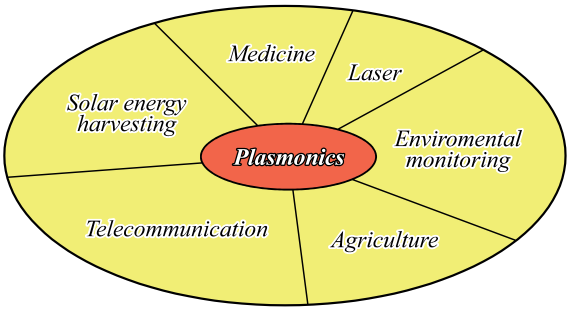

Fig. 1. Application of plasmonics discussed in this review

1. Working mechanism of plasmonic sensors

Plasmonic sensors work based on the principle of surface plasmon resonance (SPR), which is the collective oscillation of free electrons in a metal surface when stimulated by incident light [28]. The working mechanism of plasmonic sensors can be explained in the following way and shown in Fig. 2*a-c* [30].

Plasmonic sensors consist of metallic surfaces or nanostructures that support surface plasmons [31]. Common materials used include Au and Ag due to their excellent plasmonic properties in the visible and near-infrared spectral ranges. A beam of light, typically from a monochromatic source such as a laser, is directed onto the plasmonic structure [32]. The light interacts with the metal surface or nanostructures, leading to the excitation of surface plasmons at a specific resonance wavelength. At the resonance condition, the incident light couples with the surface plasmons, resulting in the formation of an evanescent wave that extends into the surrounding medium. The evanescent wave is highly sensitive to changes in the refractive index in its vicinity. When the refractive index of the surrounding medium changes, for example, due to the presence of analytes or binding events on the sensor surface, it affects the properties of the evanescent wave. The change in refractive index causes a shift in the resonance wavelength or a change in the intensity of the reflected or transmitted light. The changes in the resonance wavelength or intensity of the reflected or transmitted light are measured using optical detectors such as spectrometers or photodiodes. These measurements are then correlated with the concentration or properties of the analyte of interest. By monitoring the changes in the plasmonic response, plasmonic sensors can detect and quantify the presence of analytes or changes in the surrounding environment.

However, in the case of surface plasmon polariton (SPP) sensors consist of a WG structure, typically a thin metal film (e.g., Au or Ag) deposited on a dielectric substrate such as glass or silicon. The WG layer supports the propagation of SPPs, which are coupled EM waves involving the oscillation of free electrons at the metal-dielectric interface. The incident light, usually from a laser, is coupled into the WG structure through an optical coupling element, such as a grating or prism. The incident light excites surface plasmon polaritons at the metal-dielectric interface, creating an SPP wave that propagates along the surface. The changes in the SPP properties are measured using various techniques such as spectroscopy, interferometry, or imaging. The detection can be performed by monitoring the transmitted or reflected light from the SPP wave, or by directly measuring the SPP properties using specialized detectors [28]. The measurements are analyzed to determine the presence, concentration, or other relevant parameters of the analyte.

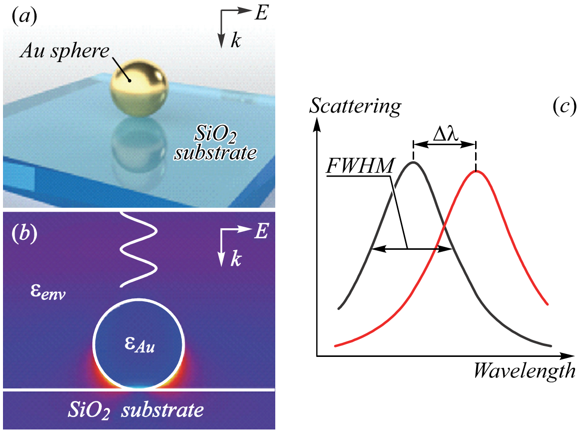

Fig. 2. (a) Working mechanism of plasmonic sensing [30], (b) E-field distribution for the sensing geometry [30], (c) scattering spectra for the plasmonic system [30]

2. Plasmonics in medicine

Plasmonic nanoparticles (such as Au) or Ag nanoparticles exhibit unique optical properties due to the localized surface plasmon resonance (LSPR) effect. These characteristics make them promising candidates for several medical applications such as: I) Plasmonic nanoparticles can absorb light at specific wavelengths, converting it into heat. This property can be utilized in photothermal therapy (PTT) [33], where nanoparticles are selectively delivered to target tissues and then irradiated with light, leading to localized heating and destruction of cancer cells or other pathological targets; II) Plasmonic nanoparticles can enhance imaging techniques, such as optical coherence tomography (OCT) [34] and photoacoustic imaging (PAI) [35]. By incorporating plasmonic nanoparticles into contrast agents, researchers can improve the sensitivity and resolution of these imaging modalities, allowing for better visualization of tissues and disease diagnosis; III) Plasmonic nanoparticles can serve as carriers for drugs or therapeutic agents. They can be functionalized with specific ligands to target specific cells or tissues. The nanoparticles can be remotely triggered by light to release the drugs, enabling localized and controlled drug delivery [36]; IV) Plasmonic nanoparticles can be utilized in biosensors for the detection of different biomarkers or analytes. The interaction between the nanoparticles and the target molecules leads to variations in the plasmonic properties, which can be measured optically. This permits for sensitive and rapid detection of diseases, such as cancer, infectious agents, or biomarkers related to specific conditions; V) Plasmonic nanoparticles can be integrated into tissue scaffolds or hydrogels to modulate cellular behavior. Light stimulation of the nanoparticles can induce localized heating, which can promote tissue regeneration, enhance cell growth, or trigger specific cellular responses.

While plasmonics in medicine shows promising potential, it is still an active area of research, and more studies are needed to fully understand its mechanisms and optimize its applications. However, these advancements hold great promise for improving diagnostics, therapies, and overall patient care in the future.

A MIM WG-based multipurpose plasmonic sensor architecture is studied numerically [37]. The suggested architecture can be used right away for temperature and biological sensing applications. The sensor is made up of two straightforward resonant cavities with a square and circular shape, one of which is connected to a MIM bus WG as shown in Fig. 3*a*. The analytes can be delivered into the square cavity for the biosensing operation, and a thermo-optic polymer can be deposited in the circular cavity to produce a variation in resonance wavelength in response to changes in ambient temperature. Both sensing techniques operate separately as shown in Fig. 3*b*. Each cavity offers a resonance dip that does not obstruct the analysis process at a specific location in the sensor's transmission spectrum. PDMS layer is deposited in the circular cavity to determine the changes in the ambient medium temperature. The influence of temperature on the refractive index of the PDMS layer is shown in Fig. 3*c*. For temperature sensing and biosensing, respectively, such a basic configuration incorporated in the single chip may be able to offer a sensitivity of 700 nm/RIU and 0.35 nm/°C. The FOM for the temperature sensing module and the biosensing module, respectively, is roughly 0.008 and 21.9. The FOM ratio measures the resonance dip's width to the device's sensitivity. The suggested sensor design can be useful in two situations: (i) when testing biological analytes must be done in a temperature-controlled environment; and (ii) for minimizing the impact of ambient temperature fluctuations on refractometric measurements in real-time mode [37].

Due to its unique dip-and-read operation style, surface plasmon devices installed at the end-facets of optical fibers are attractive options for quick and point-of-care sensing applications. Most biosensing applications are now unattainable with these devices due to their noise-equivalent limits of detection, which are significantly lower than their free-space counterparts. The construction process for a quasi-3D Fano resonance cavity is described in [38], along with improvements to the quality factor and coupling effectiveness for fiber-coupled surface plasmon resonance. The 3D-Quasi Fano resonance cavity and the reflectivity spectrum are shown in Fig. 3*d* and Fig. 3*e*, respectively [38]. The Fano resonance in this device combines a Fabry-Pérot etalon's high coupling efficiency with a plasmonic crystal cavity's high-quality factor resonance. A low-adhesion yet surface-plasmon-tunnelling interface is needed between the quasi-3D device and the flat substrate to transmit the device to a single-mode fiber end-facet. A nanocap-slit unit structure, of which the plasmonic crystal was composed, was used to realize such an interface. Experimentally, a noise-equivalent limit of detection of 10^{-7} RIU was attained, enabling the physical adsorption of bovine serum albumin to be discriminated at levels of ng/mL [38]. Thus, this study transforms fiber end-facet surface plasmon devices into one of the high-sensitivity label-free sensing technologies, overcoming the long-standing signal-to-noise ratio constraint. In addition, it offers a top-down fabrication process that makes it possible to create 3D plasmonic structures on fiber end-facets at the nanoscale scale.

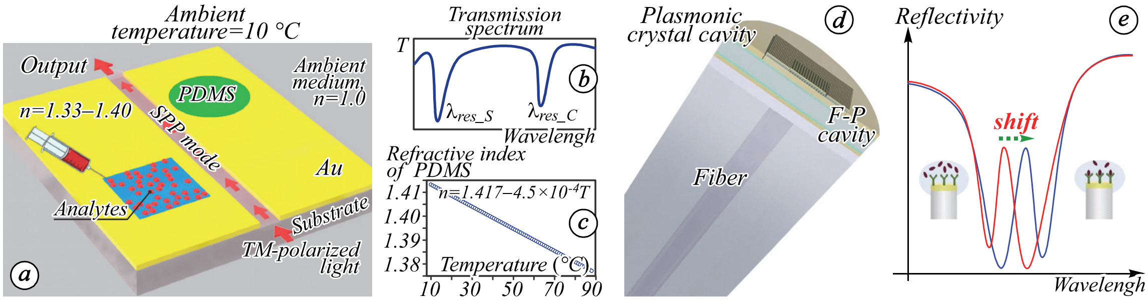

Fig. 3. Schematic of the MIM WG-based plasmonic sensor for bio and temperature sensing [37], (b) transmission spectrum [37], (c) dependence of the refractive index of the PDMS on the ambient temperature [37], (d) 3D-Quasi Fano resonance cavity on SMF end-facet [38], (e) reflectivity spectrum [38]

3. Plasmonics in solar energy harvesting

Plasmonics has also been extensively explored for its potential applications in solar energy conversion and harvesting [39]. By harnessing the unique properties of plasmonic nanoparticles, researchers aim to improve the efficiency of solar cells and enable novel energy harvesting mechanisms such as: I) Plasmonic nanoparticles can be integrated into the design of solar cells to enhance light trapping and absorption. These nanoparticles can scatter and confine light within the active layer of the solar cell, increasing the path length of photons and promoting their absorption. This leads to improved light absorption and, consequently, higher conversion efficiencies; II) Plasmonic nanoparticles can be used to enhance light absorption in thin-film solar cells [40]. By embedding or depositing plasmonic nanoparticles on or within the active layer, light can be localized and concentrated near the nanoparticles, allowing for better absorption in the thin film. This is particularly useful for materials with limited light absorption capabilities [41]; III) Plasmonic nanoparticles can generate "hot carriers" when they interact with photons. Hot carriers are high-energy electrons or holes that are formed due to the absorption of photons by plasmonic nanoparticles [42]. These hot carriers can be harvested and utilized to generate electricity or drive chemical reactions, improving the overall efficiency of solar cells; IV) Plasmonic nanoparticles can be used in up-conversion and down-conversion processes to broaden the spectral range of solar cells. Up-conversion involves converting low-energy photons into higher-energy photons, which can then be absorbed by the solar cell. Down-conversion, on the other hand, converts high-energy photons into lower-energy photons that match the absorption range of the solar cell. Both processes can enhance the utilization of a broader spectrum of sunlight, increasing the overall efficiency of solar cells [43]; V) Plasmonic nanoparticles or structures can act as concentrators, focusing light into a small area. This concentration effect can be beneficial for increasing the intensity of sunlight incident on the solar cell, thereby improving its performance [44].

It is imperative to note that while plasmonics offers exciting possibilities for improving solar energy conversion, there are still challenges to overcome, such as optimizing the design and fabrication of plasmonic structures, minimizing energy losses, and ensuring long-term stability and scalability. Nevertheless, plasmonic approaches hold the potential for enhancing the efficiency and success of solar energy technologies [45].

It has long been unclear if plasmonic nanoparticles (NPs) dispersed within a perovskite active layer can boost solar cells' efficiency [46]. It is generally known that adding metallic nanoparticles (NPs) to an active layer can raise the near-field intensity around them due to the dipolar localized surface plasmon resonance (LSPR, commonly known as the antenna effect), which can improve solar cells' ability to absorb light. It is unknown if adding plasmonic NPs to a perovskite active layer improves performance compared to a pure perovskite solar cells (PSCs) counterpart because the use of plasmonic NPs in perovskite solar cells has received little attention. By using effective medium theory and a thorough balancing analysis, the theoretical and practical boundaries of "plasmonic metamaterial" PSCs are investigated. The findings suggest that increasing the effective refractive index of perovskite using scattered plasmonic NPs can, in theory, improve solar cell efficiency. The schematic of the metamaterial PSC is shown in Fig. 4*a* [46].

Electric field intensity can be generated around or at the surface of plasmonic nanostructures because of light interaction. In the active layer of solar cells, there is a greater chance that light will be absorbed due to the electric field's increased intensity. Due to their ideal photovoltaic properties, PSCs, whose absorption edge is close to 800 nm, may be made to absorb light at longer wavelengths using plasmonic nanostructures [47]. The bulk of the perovskite solar cell is filled with plasmonic NPs of varying radii (20–60 nm), and it was discovered that the Au NPs with a radius of 60 nm boosted the absorption of the cell by 20% in comparison to the bare one without Au NPs. The schematic of the device is shown in Fig. 4*b* [47].

To increase sunlight absorption, a plasmonic aluminium nanoparticle array is integrated into standard GaAs thin-film solar cells' top surface as shown in Fig. 4*c* [40]. Such solar structures' performance is assessed by keeping track of how their absorbance changes due to altering structural factors. Over the antireflective layer, a single array of Al nanoparticles is embedded to improve the absorption spectra in the near-infrared and visible wavelength ranges. In addition, the planar density of the plasmonic layer is offered as a key variable in examining and analyzing the functionality of solar cells. Then, a double Al nanoparticle array is presented as a deviation from the typical uniform single array since it has diverse spatial distributions and particles of varying sizes. Utilizing the enhancement % in the absorption, performances were compared. The results show that adjusting solar energy harvesting is significantly influenced by the structural characteristics of the described solar cell, particularly the planar density of the plasmonic layer. Additionally, the absorption in the visible area is improved by increasing the plasmonic planar density.

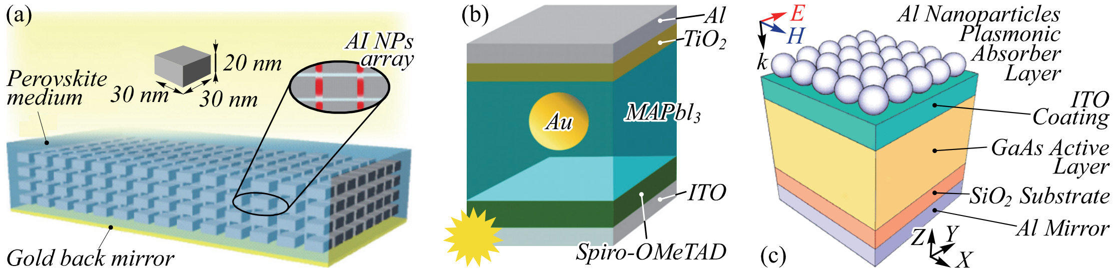

Fig. 4. (a) Schematic of plasmonic metamaterial PSC [46], (b) The schematic of the PSC with an Au NP [47], (c) A schematic diagram of thin-film GaAs solar cells having Al NP array placed both on top surface [40]

4. Plasmonics in environmental monitoring

From the perspective of environmental monitoring, plasmonics offers distinctive capabilities for detecting and analyzing various pollutants, contaminants, and environmental parameters [48]. For instance:

I) Sensing of pollutants: Plasmonic sensors can be designed to detect and quantify the presence of specific pollutants, such as heavy metals, organic compounds, and gases, in the environment. The interaction between plasmonic nanostructures and the target analyte leads to changes in the optical properties, such as the absorption or scattering of light, which can be measured and correlated with the concentration of the pollutant.

II) Water quality monitoring: Plasmonic-based sensors can be employed for real-time monitoring of water quality parameters, including pH, salinity, turbidity, and dissolved oxygen levels [49]. By integrating plasmonic nanostructures with microfluidic devices or optical fibers, it becomes possible to create compact and sensitive sensors for on-site or in situ measurements.

III) Air pollution monitoring: Plasmonic sensors can be utilized to detect and monitor air pollutants, such as volatile organic compounds (VOCs), particulate matter, and nitrogen dioxide (NO_2). Plasmonic devices can be integrated into portable monitoring systems for continuous air quality assessment in urban areas or industrial settings [50].

IV) Environmental sensing platforms: Plasmonic nanostructures can be incorporated into multifunctional sensing platforms that combine different types of sensors to monitor various environmental parameters simultaneously. For example, plasmonic sensors can be integrated with electrochemical or biological sensors to create hybrid devices for comprehensive environmental monitoring [51].

V) Remote sensing: Plasmonics can also be utilized for remote sensing applications, enabling the detection, and monitoring of environmental conditions from a distance. By exploiting the plasmon resonance phenomenon, it is possible to enhance the sensitivity and selectivity of remote sensing techniques, such as surface-enhanced Raman spectroscopy (SERS) or infrared absorption spectroscopy.

Usually, plasmonics offers promising opportunities for improving environmental monitoring capabilities. The ability to design plasmonic nanostructures with tailored optical properties and their compatibility with various sensing platforms make them attractive for applications in environmental science and pollution control [52]. Ongoing research in this field aims to develop more sensitive, selective, and cost-effective plasmonic-based sensors for environmental monitoring purposes [53].

The need for quick, uncomplicated detection techniques for water quality monitoring arises from the possibility of water contamination outbreaks. Due to their distinctive LSPRs, plasmonic nanostructures like AuNPs and AgNPs provide strong candidates for the creation of extremely sensitive biosensors. In the visible and infrared light spectrum, the LSPR of AuNPs and AgNPs is dependent on the composition, size, shape, environment, and aggregation state of these NPs. A colourimetric sensor may be made using this plasmonic activity as the basis for environmental analysis. Additionally, the EM-field close to the NP surface is improved by the LSPR, which forms the basis for surface-enhanced Raman spectroscopy (SERS) based detection [53].

Refractive index variations caused by gas are found using high-resolution localized surface plasmon resonance (HR-LSPR) spectroscopy on arrays of silver nanoparticles (Fig. 5*a*) [54].

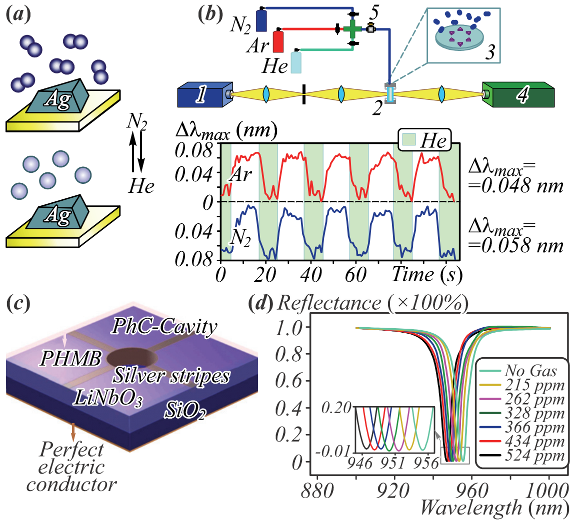

Fig. 5. (a) Refractive index gas sensing with AgNP [54], (b) Resonance position of the Ag nanoparticles over time as the gas transfers between He/Ar and He/N_2 [54], (c) PhC cavity-based-plasmonic gas sensor [19], (d) Reflection spectrum [19]

The scientists created Ag nanoparticle arrays for gas sensing studies using nanosphere lithography, and then they collected extinction spectra while continuously switching the gaseous environment between helium/argon and helium/nitrogen every 10 s. When switching from He to the target gases, distinct spectral redshifts are seen, with wavelength shifts of 0.048 nm and 0.058 nm for Ar and N_2, respectively, which translates to a sensitivity of around 200 nm/RIU (Fig. 5*b*) [54]. The scientists also carried out gas exchanges every 5s and discovered mass-transport limited rise and fall timings, pointing to the detection of RI changes in the gaseous environment as opposed to adsorption processes at the Ag surface. The use of silver for plasmonic resonators with low inherent damping, the stability of their experimental apparatus, and the capacity to precisely trace the plasmon resonance wavelength throughout several tests were the primary enabling elements in their high-resolution studies.

For carbon dioxide (CO_2) gas detection, a perfect absorber with a photonic crystal cavity (PhC-cavity) is numerically studied [19]. Silver-based metallic structures are used to harness plasmonic phenomena and achieve perfect absorption. The sensor has a PhC-cavity, Ag stripes, and Polyhexamethylene Biguanide (PHMB) polymer placed on its surface as the host functional material as shown in Fig. 5*c*.

The PhC-cavity, which is positioned in the cell's center, aids in allowing EM waves to reach the structure's sublayers. Because of this, when the CO_2 gas levels rise, the host material's refractive index falls, shifting the device's resonant wavelength from red to blue and vice versa as shown in Fig. 5*d*. With a maximum sensitivity of 17.32 pm/ppm attained for a concentration of 366 ppm and a FOM of 2.9 RIU^{-1}, the sensor is utilized to detect CO_2 gas concentrations between 0 and 524 ppm. By adopting the appropriate host functional materials, the four-layer device's simple and small architecture may be used to a variety of sensing applications [19].

5. Plasmonics in lasers

Plasmonics, which is the study of the interaction between EM waves and free electrons in metal nanostructures, can indeed be applied in lasers [55]. Plasmonics in lasers involves utilizing plasmonic effects to enhance various aspects of laser operation, such as light confinement, absorption, emission, and modulation [56]. One area where plasmonics is extensively used in lasers is in the field of surface plasmon-enhanced lasers [57]. Surface plasmons are collective oscillations of electrons at the interface between a metal and a dielectric material. By carefully designing the metal-dielectric interface, it is possible to couple light-to-surface plasmons, enabling efficient light-matter interaction. The integration of plasmonic structures into lasers can offer several benefits, including I) Enhanced light confinement: Plasmonic structures can confine light to subwavelength scales, enabling the generation of highly localized EM fields and enhancing the interaction between light and gain material; II) Increased absorption: Plasmonic structures can enhance the absorption of light by effectively concentrating the incident light into the active medium of the laser; III) Improved emission: Plasmonics can enhance the spontaneous emission rate of light sources, leading to increased photon generation and improved laser efficiency; IV) Enhanced modulation: Plasmonics can enable the control of light properties, such as intensity, polarization, and phase, through active manipulation of the plasmonic structures. This capability can be utilized for on-chip modulation and signal processing applications. By incorporating plasmonic effects into lasers, researchers aim to improve their performance parameters, including output power, efficiency, and beam quality. Plasmonic lasers find applications in various fields, including telecommunications, sensing, imaging, and integrated photonics.

The first plasmonic nanolasers, also known as "Spasers", were separately demonstrated by three teams, each with different goals and viewpoints as shown in Fig. 6*a-c* [58 – 60]. These plasmonic nanolasers are incredibly small coherent light sources with incredibly quick dynamics and a wide range of interesting potential uses [61]. A metal nanosphere served as the plasmonic core of the first localized surface plasmon (LSP) spaser, which was encased in a dielectric shell that contained a gain material, usually dye molecules. Since then, reports of other nanoshell LSP spasers have been made. These spasers, which range in size from several to tens of nanometers, are the smallest coherent generators created to date. A surface plasmon polariton (SPP) mode propagates in one of the dimensions of the devices that were initially referred to as plasmonic nanolasers, which are based on semiconductor-metal plasmonic gap modes. The sole difference between these SPP nanolasers and spasers regarding the physics at play is whether localized or travelling plasmon modes are engaged.

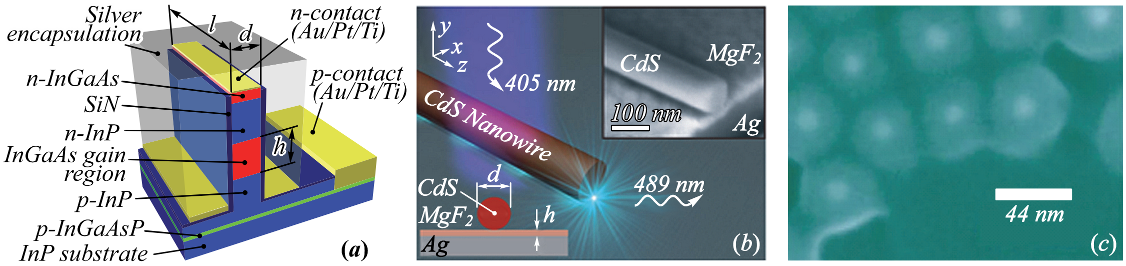

Fig. 6. (a) Nanolaser based on a metal-insulator-semiconductor-insulator-metal plasmonic gap mode, where vertical confinement was accomplished via a double heterostructure [58], (b) Plasmonic nanolaser based on a two-dimensionally confined nanowire plasmonic mode [59], (c) Spaser established on a three-dimensionally confined metal nanoparticle mode [60]

6. Plasmonics in telecommunication

Plasmonics has promising applications in the field of telecommunications, offering potential benefits for data transmission and manipulation at nanoscale dimensions. Traditional optical WGs, such as optical fibers, have limitations in terms of their size and confinement of light to subwavelength scales [62]. Plasmonic WGs, on the other hand, utilize surface plasmons to confine light to nanoscale dimensions, allowing for the transmission of light signals in compact structures. Plasmonic WGs can enable highly integrated photonic circuits and contribute to the development of on-chip optical communication systems [63].

Modulators are key components in telecommunication systems for manipulating the intensity, phase, or polarization of light signals. Plasmonic structures can be used as active elements in modulators to achieve efficient light modulation at the nanoscale [64]. By exploiting the strong light-matter interaction and field confinement provided by plasmonics, researchers are developing plasmonic modulators with high modulation speeds, compact size, and low power consumption.

Plasmonic antennas can be used for efficient coupling of light between free-space and nanoscale devices, enabling enhanced transmission and reception of optical signals [65]. Plasmonic antennas can improve the efficiency of optical communication links, particularly for applications involving nanoscale components and integration with on-chip photonic systems.

Plasmonic filters are an emerging technology that shows promise for various applications, including telecommunications [66]. Plasmonic filters can be employed to control the transmission and manipulation of light signals in optical communication systems [67]. They offer several advantages over conventional filters, such as smaller sizes, higher efficiency, and the ability to operate at nanoscale dimensions. Wavelength Division Multiplexing (WDM) is a technique used to transmit multiple wavelengths of light simultaneously through a single optical fiber. Plasmonic filters can be employed to separate different wavelengths and selectively direct them to specific destinations, enabling efficient multiplexing and demultiplexing of signals [68].

Moreover, plasmonic filters can be utilized as active components in optical switches. By leveraging the tunability of plasmonic structures, these filters can control the routing of optical signals, allowing for fast and efficient switching between different transmission paths.

Furthermore, plasmonic effects can be employed to develop highly sensitive sensors for telecommunications applications. Plasmonic sensors utilize the interaction between light and plasmons to detect changes in the refractive index of the surrounding environment. This enables the detection of minute changes in chemical or biological samples, which find applications in areas such as environmental monitoring, biomedical diagnostics, and telecommunications network monitoring [69].

Plasmonic devices and components offer the potential for high-speed, compact, and efficient data transmission and manipulation, contributing to the advancement of next-generation communication systems [70, 71]. Ongoing research in plasmonics continues to explore new concepts and designs to further improve the performance and integration of plasmonic devices in telecommunication applications.

In [72], novel non-volatile combinational and sequential logic circuit topologies are introduced, together with non-volatile hybrid electro-optic plasmonic switches. A plasmonic WG with a thin layer of a phase-change material (PCM) makes up the electro-optic switches as shown in Fig. 7*a* [72]. By switching the PCM's phase from amorphous to crystalline and back again, the optical losses in the WG can be reduced. Electrical threshold switching, thermal conduction heating using external electrical heaters, or the plasmonic WG metal itself as an integrated heater are all possible ways to implement the phase transition process in the PCM. It is shown that plasmonic switches can be used as the active components in all logic gates, a half-adder circuit, and sequential circuits. Furthermore, the plasmonic switch designs and logic implementations exhibit minimum extinction ratios greater than 20 dB, compact designs, low operating power, and high-speed implementations. On the same platform, photonics, plasmonics, and electronics are coupled to create a powerful architecture for logic operations [72].

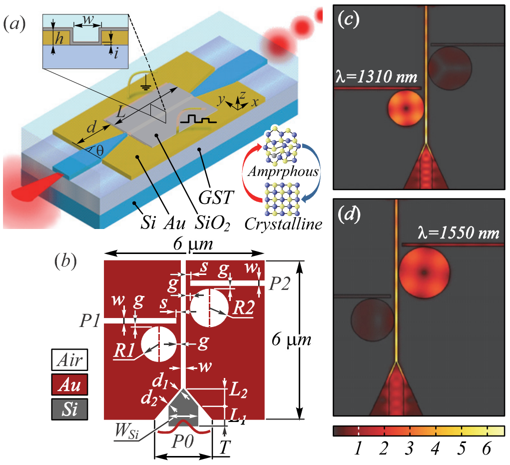

Fig. 7. (a) Schematic of a broadband non-volatile hybrid electro-optic plasmonic switch [72], (b) 1x2 demultiplexer design for telecommunication applications [15], (c, d) E-field distribution at the operational wavelength of 1310 nm and 1550 nm, respectively [15]

A compact 1×2 plasmonic demultiplexer based on a MIM WG is discussed in a numerical study [15]. The bus WG is side linked to two hollow circular cavities on either side as shown in Fig. 7*b*. The cavities are made to resonate at 1310 nm and 1550 nm, which are the appropriate working wavelengths. Previous research hasn't taken the mechanics of light coupling to a MIM WG into account. To efficiently transform a dielectric into a plasmonic mode, a silicon tapered mode converter and plasmonic demultiplexer are combined. The device has a 6 µm by 6 µm footprint. Crosstalk at the output port (P1) and output port (P2) is 14.07 dB and 13.67 dB, respectively for transmission wavelengths of 1550 nm and 1310 nm. The E-field distribution at the operational wavelength of 1310 nm and 1550 nm is shown in Fig. 7*c* and Fig. 7*d*, respectively [15].

7. Plasmonics in agriculture

Plasmonic nanoparticles can be used to increase the efficiency of photosynthesis in plants. These nanoparticles can absorb and scatter light in a controlled manner, increasing the amount of light available to the plants for photosynthesis [73]. By optimizing the absorption and scattering properties of nanoparticles, plasmonics can potentially enhance crop yields. Plasmonic sensors can be developed to detect various parameters relevant to agriculture, such as soil quality, nutrient levels, and the presence of contaminants or pathogens. These sensors utilize the unique optical properties of plasmonic nanoparticles to provide rapid and sensitive detection, enabling farmers to monitor their crops and make informed decisions regarding fertilization, irrigation, and disease management [74].

Plasmonics can be employed to improve the targeted delivery of agrochemicals, such as pesticides and fertilizers, to plants. By attaching nanoparticles to these chemicals, their absorption and distribution can be controlled [75]. This targeted delivery minimizes the use of chemicals, reduces environmental impact, and enhances the effectiveness of crop protection and nutrient management. Plasmonics can contribute to disease management in agriculture by enabling the development of rapid and sensitive diagnostic tools. By utilizing plasmonic biosensors, it is possible to detect the presence of pathogens or disease-related biomarkers in plants or the surrounding environment at an early stage. This early detection facilitates prompt action, such as implementing quarantine measures, targeted treatments, or adjusting cultivation practices. Plasmonics has the potential to enhance the genetic modification of crops. By using plasmonic nanoparticles, gene delivery systems can be developed that improve the efficiency of genetic transformation in plants [76]. This can enable the development of crops with improved traits, such as disease resistance, stress tolerance, and increased productivity.

Hyperspectral imaging is a technology that can provide valuable insights and benefits in agriculture [77]. It involves capturing and analyzing a wide range of EM wavelengths across the visible and infrared spectrum. Hyperspectral imaging can detect subtle changes in plant health by measuring the reflectance or absorption of light by crops. It can identify stress factors such as nutrient deficiencies, water stress, disease, or pest infestation at an early stage, allowing farmers to take timely action. It can help identify specific spectral signatures associated with plant diseases or pest infestations. By scanning crops with hyperspectral cameras or mounted sensors, farmers can detect infected or infested areas and apply targeted treatments, reducing the need for broad-spectrum pesticides.

By analyzing hyperspectral data, it is possible to estimate crop yield and quality parameters [77]. Different plant characteristics, such as leaf chlorophyll content, biomass, or fruit ripeness, can be assessed, enabling farmers to make informed decisions regarding harvesting and yield optimization. Hyperspectral imaging can provide detailed information about soil composition, moisture content, and nutrient levels. By analyzing the reflected light from the soil, it is possible to assess soil fertility, identify areas with nutrient deficiencies, or detect soil contamination. This information helps farmers optimize fertilizer application and irrigation practices.

Hyperspectral imaging can aid in identifying and mapping weeds within a field. Different plant species exhibit unique spectral signatures, allowing farmers to differentiate between crops and weeds. This information can be used to develop targeted weed control strategies, reducing herbicide usage and minimizing crop damage. It enables detailed characterization of plant traits, including leaf area, leaf angle, biomass, and canopy structure. These measurements assist in crop breeding programs, where researchers aim to develop plants with desirable traits such as drought resistance, disease tolerance, or improved yield potential.

By integrating hyperspectral imaging with other geospatial technologies like GPS and drones, farmers can create high-resolution maps of their fields. These maps provide valuable information on crop variability, enabling site-specific management practices such as variable rate application of fertilizers, irrigation, or plant protection products. In [78], four distinct photodetectors with wavelengths between 750 nm and 1900 nm were shown by the researchers. Specific frequencies of incoming light were absorbed by the detectors' plasmonic metasurfaces, which heated them. A very thin layer of pyroelectric material (aluminium nitride) that was directly beneath the metasurfaces saw a change in its crystal structure because of the heat. A lower layer, a silicon semiconductor layer, reads the voltage produced by the structural change and transferred it to a computer for analysis.

Based on the technique, the authors anticipate a variety of possibilities for commercial cameras since producing photodetectors require a quick, low-cost, and scalable manufacturing method [78]. Precision agriculture was the researchers' primary goal, but the integration of several photodetectors with various frequency responses on a single chip might enable lightweight, affordable multispectral cameras for applications including cancer surgery, food safety inspection, and the team's initial focus. A low-cost, handheld detector can be realized that could take pictures of crop fields from the air or low-cost drones. Precision agriculture could be made possible by a new kind of lightweight, affordable hyperspectral camera. Fig. 8 demonstrates how individual pixels may be set to light frequencies that represent the diverse requirements of a crop field [79].

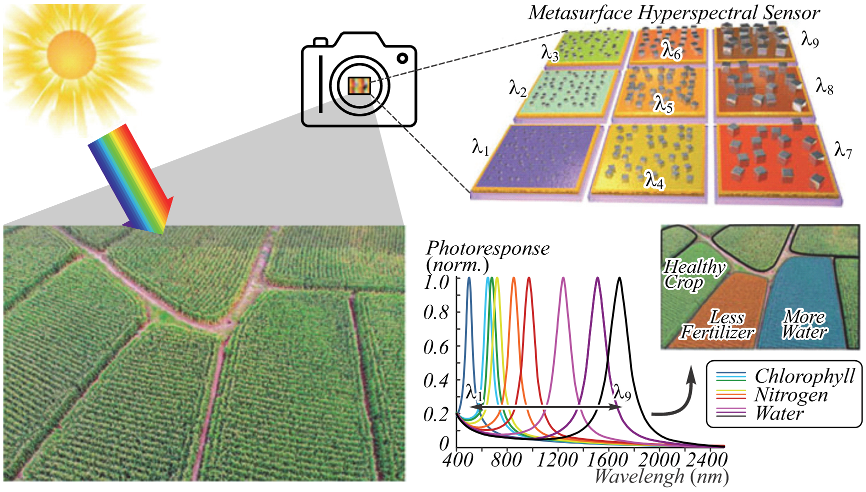

Fig. 8. Utilization of plasmonic-based light detector in precision agriculture [79]

8. Author's viewpoint on the advantages and limitations of plasmonic devices

Plasmonics is considered a promising field for various applications due to its potential to manipulate and control light at the nanoscale [80]. It encompasses the study and utilization of surface plasmons, which are collective oscillations of electrons on the surface of metals when excited by photons. Plasmonics facilitates strong interaction between light and matter by concentrating EM fields in nanoscale regions. This property can be harnessed to enhance light absorption, scattering, and emission processes, enabling advancements in various fields such as biosensing, imaging, food safety, environmental monitoring and energy harvesting [18, 21].

Plasmonics holds the potential to revolutionize data communication by enabling ultrafast optical information processing and transmission [81]. Surface plasmons can carry information at extremely high speeds, surpassing the limitations of conventional electronic devices. Plasmonic WGs and interconnects could lead to faster and more efficient data transfer in next-generation computing systems.

Plasmonic nanostructures exhibit unique optical properties that make them highly sensitive to changes in their local environment. This sensitivity can be leveraged for ultra-sensitive sensing and detection of various analytes, including biological molecules, gases, and chemicals. Plasmonic sensors offer the potential for rapid and accurate diagnostics in fields such as healthcare, environmental monitoring, and food safety.

Plasmonics can be integrated with existing photonic technologies to create hybrid systems that combine the best attributes of both. By merging plasmonics with conventional optics, it becomes possible to overcome some of the limitations of each technology. This integration can lead to the development of advanced devices with improved performance and functionality [82].

Plasmonics has the potential to impact renewable energy technologies by improving light absorption and energy conversion efficiency in solar cells. Plasmonic nanostructures can be designed to enhance light absorption and trapping, enabling the development of more efficient photovoltaic devices. Additionally, plasmonics can contribute to the field of catalysis by enhancing light-driven chemical reactions for applications such as water splitting and pollutant degradation.

While plasmonic devices hold great promise, they also have certain limitations that need to be addressed for their widespread implementation. Plasmonic materials, typically metals such as Au and Ag, exhibit significant energy losses due to ohmic heating and radiation damping [83]. These losses can limit the efficiency of plasmonic devices, leading to decreased performance and increased heat generation. Managing and minimizing these losses is a critical challenge in the development of practical plasmonic devices.

Fabricating precise nanostructures with well-controlled dimensions and configurations can be challenging and expensive. The nanoscale features required for plasmonic devices often necessitate advanced lithography techniques and complex fabrication processes. Achieving large-scale production of plasmonic devices with high yield and reproducibility remains a significant hurdle [84].

Integrating plasmonic devices with existing technologies, such as electronic circuits or optical WGs, can be challenging but achievable. Plasmonic components typically operate at different wavelengths and have different characteristics than their electronic or photonic counterparts. Developing effective methods for seamless integration and overcoming impedance mismatches is a complex task.

Plasmonic devices often have limited dynamic control over their optical properties. Once the nanostructures are fabricated, their properties are fixed. However, many applications require the ability to dynamically control plasmonic resonances, such as switching, modulation, or tuning. Developing methods for active and reversible control of plasmonic devices is an ongoing research area [85].

Plasmonic devices can suffer from crosstalk or interference effects due to their strong field confinement and interactions [86]. Unintended coupling between neighbouring plasmonic components or unintended excitation of unwanted resonances can impact device performance and signal integrity.

It is worth documenting that research efforts are ongoing to address these limitations. New materials, fabrication techniques, and design strategies are being explored to enhance the performance, efficiency, and functionality of plasmonic devices [87]. Overcoming these challenges will be crucial for the broader implementation of plasmonics in practical applications.

Abbreviations

Electromagnetic = EM; Metal-insulator-metal = MIM; Waveguide = WG; Gold = Au; Silver = Ag; Surface plasmon polariton = SPP; Surface plasmon resonance = SPR; Localized surface plasmon resonance = LSPR; Optical coherence tomography = OCT; Photothermal therapy = PTT; Polyhexamethylene Biguanide = PHMB; Perovskite solar cell = PSC; Nanoparticle = NP.

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