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From Materials to Methods: The Role of Plasmonics in Modern Sensing Applications

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Abstract: This systematic review aims to comprehensively explore the evolution of plasmonic sensors from their initial designs to the latest applications. Plasmonics supports the features of sub- wavelength confinement. The most promising aspect of sub-wavelength light transmission is its ability to combine the advantages of optical and nanotechnology. Traditional optical device-based sensors are limited by the diffraction limit, so in this paper, we give a brief overview of the fundamentals of plasmonics. Their various structural configurations, including ring waveguides, silicon-based waveguides, array-based structures, photonic crystal-based structures, and cavity-based structures, have been discussed. The two most popular techniques for plasmon excitation are covered: the first is the wavelength interrogation technique, and the second is the angular interrogation technique. Additionally, a summary of the refractive index sensor's key properties, including sensitivity, resolution, figure of merit, Q-factor, repeatability and accuracy also discussed. It elaborates the properties of many plasmonic materials, including gold and silver. The most crucial element in determining the functioning of the sensor is sensitivity. Therefore, we examine many topologies used in simulate the plasmonics based refractive index sensor, their merits and demerits, their performance parameter, the outcomes of some important works and the author's critical observation behind the research are analyzed. The unique optical properties of plasmonic nanostructures have enabled the development of sensors that hold immense promise for applications in diverse fields such as medical imaging, environmental monitoring, food safety, and more.

Keywords: *Metal-insulator-metal waveguide, Resonator, Ring waveguide, Sub-wavelength confinement.*

1. Introduction

In recent years, the field of Plasmonics has emerged as a pioneering avenue of research that bridges the gap between photonics and nanotechnology. This rapidly evolving field explores the unique interactions between electromagnetic waves and free electrons, known as plasmons, at the nanoscale [1]. These interactions give rise to fascinating phenomena, enabling researchers to manipulate light in unprecedented ways and catalyzing breakthroughs in various scientific and technological domains [2]. At its core, Plasmonics investigates the collective oscillations of free electrons at the interface between a metal and dielectric material [3]. These oscillations generate localized surface plasmon resonances confining electromagnetic energy to sub-wavelength dimensions and granting the ability to manipulate light beyond the diffraction limit [4]. Plasmonics supports two phenomena for this confinement of light signal in nano-sized devices [5]. One is based on locally generated surface plasmons, while the other is based on propagating surface plasmons. The process of localized surface plasmons involves trapping incident light inside nanoparticles, and the trapped light has a shorter wavelength than the original light [6]. In SPP, the propagating plasmons have numerous uses in designing optical circuits, gates, routers, sensors, etc. If metal-insulator-metal (MIM) geometry is utilized, deep sub-wavelength confinement and wave guiding features are accomplished by MIM waveguide [7].

Nowadays, plasmonic-based sensors have garnered significant attention due to their remarkable capabilities in detecting and characterizing a wide range of analytes beyond the diffraction

limits with high sensitivity and specificity [8]. These sensors are based on surface plasmon resonance (SPR) principles [9]. In Plasmonics, the Kretschmann arrangement and Otto configuration are classical methods to generate the Plasmon at the interface [10]. These setups are designed to investigate the interaction of light with surface plasmon waves at the interface between a metal and a dielectric medium. They are widely used for studying various

Phenomena, including sensing applications and characterization of thin films. For the Kretschmann configuration, there is a combination of air-metal-prism [11]. This thin metal film is sandwiched between air and glass prism [12]. Reflection occurs when the incidence angle of light is larger than the critical angle [13]. Incident light, usually from a laser source, is directed onto the metal-dielectric interface through the prism at a specific

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incidence angle known as the resonance angle [14]. At the resonance angle, the incident light couples with the surface plasmon waves [15], leading to a sharp dip in the reflected light intensity, this is detected and used for analysis [16]. Due to its high sensitivity to changes at the metal-dielectric interface and simple setup configuration, it is suitable for sensing applications. In the Otto setup, the air interface isolates the metal layer and prism. [17]. Incident light is directed onto the metal film through the glass substrate at a specific angle of incidence. The reflected light intensity is monitored as a function of angle, and the resonance angle corresponds to the coupling of light to surface plasmon waves [18]. Appropriate assigning the air gap size between prism and metal is critical, so the Otto configuration is not precisely used in different sensing applications. However, this method can be used to study interactions between the plasmonic field and the sample medium in confined spaces [19]. The refractive index of the analyte and the sensing medium mainly determines the resonance state. The Drude model can visualize the relationship between a metal's dielectric constant and wavelength [20] is:

$$\varepsilon_m = \varepsilon_{\infty} - \frac{\omega_d}{\omega(\omega+i\omega_d)} - \frac{\Delta\varepsilon\Omega_l^{2}}{(\omega^2-\Omega_l^2)+i\Omega_l\omega} \quad (1)$$

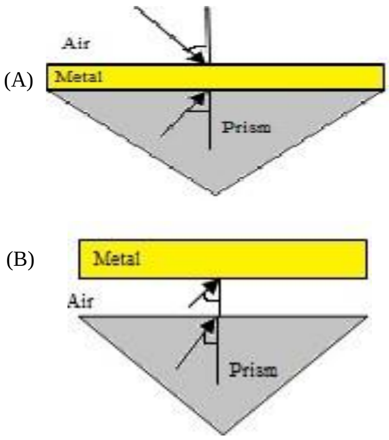

FIG. 1. EXCITATION OF SURFACE PLASMON POLARITRON IN PRISM BASED COUPLING (A) KRETSCHMANN CONFIGURATION (B) OTTO CONFIGURATIONS [5-7].

Light is launched from the polychromatic light source. There are two methods for the excitation of surface Plasmon: (1) wavelength Interrogation Method. (2) Angular Interrogation method [22]. The angular interrogation method involves monitoring the angle at which the minimum reflected light intensity occurs. In this method, the incident light's incidence angle is changed to achieve resonance with the surface plasmon waves [23]. When the resonance condition is met, the reflected light intensity decreases due to the energy transfer from the incident light to the plasmon waves [24]. In the wavelength interrogation method, the incident angle is fixed at the resonance angle, and the wavelength of the incident light is varied. As the wavelength is scanned across a range, the intensity of the reflected light is measured. The wavelength at which the power reaches a minimum corresponds to the resonance condition for surface plasmon excitation—changes in the refractive index at the metal surface lead to shifts in the resonance wavelength [25]. In this paper, we discuss the basic concept of Plasmonics, different applications of plasmonic-based sensors, their different configuration, sensor parameter, and their advantages and disadvantages. This review article explores the theoretical foundations of plasmonics, highlighting essential ideas including plasmon propagation, resonance conditions, the interaction of plasmons with nanoscale structures, and plasmonics-based refractive index sensors.

1.1 Optical Sensors

Since the 18th century, optical sensing approaches have played a vital role in environmental monitoring, medical diagnosis, irrigation, nanoscience, etc. [26]. Optical sensors continue to evolve with advancements in materials science, nanotechnology, and photonics, enabling them to address increasingly complex sensing challenges across various industries. Optical sensors are transducers that convert photons into electronic signals, whereas plasmonic signals convert plasmons into high-energy signals. There are many different optical techniques; however, researchers are leaning toward plasmonics-based optical sensors [27]. Due to its remarkable ability to get beyond the diffraction limit and transmit signals in the sub-wavelength region, Surface Plasmon Polariton (SPP) technology is in high demand in plasmonic sensing [28]. Plasmonics-based refractive index sensors continue to be an active research and development area, with efforts focused on optimizing sensitivity, selectivity, and integration into practical sensor devices [29]. The field of Plasmonics offers a versatile platform for innovative sensing solutions in various scientific and technological domains. Plasmonics sensors have different geometrical structures like photonic crystal-based sensors, Metal-Insulator (MIM) based sensors, ring waveguide-based sensors, Insulator-metal- insulator-based sensors, cavity-based sensors, photonics waveguide-based sensors, array-based sensors, etc. [30]. The ring waveguide-based sensor has the highest sensitivity compared to the cavity-based due to its minimized size [31]. The sensor's performance depends on different parameters [32], such as choice of plasmonic material, range of analyte, wafer dimension, and combination of an optical device with resonator and their geometrical configuration—proper selection of metal layer affects the calibration of sensor efficiency and sensitivity [33-34]. Many noble metals can be used for sensing; gold and silver are the most popular metals [35]. Ag is most commonly used due to low cost, low optical damping, high sensitivity, sharp spectral response, and low power required near-infrared region due to its smallest imaginary part relative permittivity [36]. Gold (Au) also has the advantage of chemically inert properties, so it is also a good choice as a plasmonic material [37]. The IMI structure offers low losses, but the sub- wavelength confinement features is absent making them unsuitable for various sensing applications. The MIM structures provide sub-wavelength confinement, making them the structure most appropriate for sensing.

2. Performance Parameters of Sensors

2.1 Sensitivity:

The most crucial factor in analyzing any sensor's performance is its sensitivity. The observable change in the output signal for a unit change in the measurement in the analyte is referred to as the sensor's sensitivity [38]. Having high levels of sensitivity is a desirable trait. It can be measured manually or by experimentation. The sensitivity magnitude is affected by various factors, including the surrounding medium, its geometrical characteristics, wavelength range, wafer characteristics, and the type of light source [39]. The sensitivity of a fiber optic SPR sensor is measured as the change in resonance wavelength for each unit change in the analyte's refractive index. It can be represented as [40]:

$$S = \Delta\lambda / \Delta n_a \qquad (2)$$

Here, $\Delta\lambda$ is the resonant maximum wavelength shift, and Δn_a is the analyte refractive index variation [41]. The sensitivity also depends on the confinement loss and configuration of the plasmonic structure, so a suitable design with optimized parameters is preferred to get a high sensitivity value [42]. The sensitivity of plasmonic-based refractive index sensors can be very high, often detecting changes on the order of 10^-6 to 10^-7 refractive index units (RIU) or even smaller. The specific sensitivity depends on the design of the plasmonic structure and the experimental conditions [43].

2.2 Q-Factor:

Q-factor is correlated to the 3 dB bandwidth of the resonance dip ($\Delta\lambda$) . A high Q factor is desirable for a high-performance sensor. The sharp drop in the losses graph is related to the slight wavelength shift with maximum accuracy. The q factor is also associated with the FOM [44]. A few factors impact the FOM, including the sensor's configuration and geometry, the resonator's height and width, and the analyte concentration [45]. Achieving a high Q-factor in plasmonic sensors involves careful design of the plasmonic nanostructures, choosing materials, and optimizing experimental conditions. Factors such as geometry, material properties, and coupling between plasmonic structures and incident light can influence the Q-factor [46].

2.3 Resolution:

The resolution of a plasmonic refractive index sensor refers to its ability to detect and distinguish small changes in the refractive index of the surrounding medium [47]. It is typically quantified as the slightest change in refractive index that the sensor can reliably detect and measure. The resolution of a plasmonic sensor depends on various factors, including the sensor's design, the quality of the plasmonic resonance, the detection technique used, and the noise level of the measurement system [48]. The sharpness and width of the plasmonic resonance curve play a significant role in determining the resolution. Higher resolution in plasmonic refractive index sensors allows for more precise measurements and the detection of more minor changes in the surrounding medium [49]. The resolution reveals a detector's output characteristic. The resolution of a sensor is described as [50]:

$$S_r = \frac{\Delta n_a \, \Delta\lambda_{min}}{\Delta\lambda_{peak}} \qquad (3)$$

Where Δn_a shows the difference in the analyte concentration, $\Delta\lambda_{min}$ shows the least amount of wavelength shift, and $\Delta\lambda$ max leads the maximum change in resonance wavelength. The wavelength range at which the plasmonic resonance is being probed also affects the resolution.

2.4 Repeatability:

The repeatability of a plasmonic-based refractive index sensor refers to its capacity to provide accurate readings during repeated testing of the same refractive index circumstances [51]. In other words, a sensor with strong repeatability will produce consistent findings when repeatedly measuring the same sample or analyte under the same circumstances. Any sensing equipment must have repeatability since it assures measurement accuracy and dependability over time and across several investigations. A suitable sensor must have high repeatability and increase the durability of the sensor [52]. The sensor's performance remains excellent, with a high degree of repeatability [53].

The manufacturing process of the plasmonic sensor can impact its repeatability. Consistency in producing identical or highly similar sensor structures is essential for consistent sensor performance [54]. Proper sample handling techniques should be employed to avoid variations between measurements [55]. Regular calibration of the sensor against known refractive index standards helps maintain accuracy and repeatability. Proper alignment, stability, and data acquisition techniques contribute to repeatability. In some cases, the samples might have inherent variability due to their nature. Understanding and accounting for sample variability is essential for interpreting measurement repeatability [56].

2.5 Accuracy:

The sensor's accuracy defines how well it can estimate the deviation between the observed and reference analyte concentrations [57]. The accuracy of a plasmonic refractive index sensor refers to how closely its measurements align with the actual or reference values of the refractive index being measured. Achieving high accuracy is essential for obtaining reliable and trustworthy results in various applications such as bio-sensing, environmental monitoring, and material characterization [58].

To assess the accuracy of a plasmonic refractive index sensor, researchers often compare its measurements to reference values obtained from established techniques or standard samples with known refractive indices. Statistical analysis can quantify the accuracy of the sensor's measurements [59]. The design of the plasmonic sensor, including its geometry, materials, and fabrication techniques, can impact its accuracy. Well-designed sensors with optimized plasmonic properties are more likely to yield accurate measurements [60]. The choice of detection technique, such as transmission, reflection, or scattering measurements, can affect accuracy. Some designs have inherent limitations or susceptibility to errors. Accurate data analysis methods are essential for obtaining reliable results [61]. Proper algorithms, calibration curves, and correction techniques contribute to the precise interpretation of measurement data. Achieving high accuracy in plasmonic refractive index sensing involves carefully considering sensor design, calibration procedures, environmental control, and data analysis techniques [62].

2.6 Figure of Merit (FOM):

A plasmonic-based refractive index sensor's figure of merit (FoM) evaluates its performance by considering its sensitivity and capacity to distinguish minute changes in refractive index from measurement noise [63]. The sensor is more effective and efficient at detecting and measuring changes in the surrounding medium's refractive index if its merit figure is higher [64]. It is used to assess the performance of sensors and is defined as the wavelength sensitivity to the 3 dB bandwidth of the reflection spectrum [65].

$$FOM = \frac{S}{FWHM} \tag{4}$$

FWHM is the spectra's full-width half maximum (FWHM), and S is the wavelength interrogation sensitivity. The sensor's FOM is a critical component [66]. Additionally, it assesses the sensing capability using the spectral width as a benchmark [67]. It also has to do with the sensor's level of quality. A suitable sensor consistently exhibits the spectrum's full width at half maximum (FWHM) and high sensitivity, resulting in a high FOM [68]. The figure of merit can vary depending on the plasmonic-based sensor's specific design, materials, and measurement conditions [69]. The choice of detection technique (transmission, reflection, scattering, etc.) and the operating wavelength range can also influence the figure of merit. When designing or evaluating a plasmonic refractive index sensor, optimizing its sensitivity, spectral characteristics, and noise levels is crucial to achieving the highest possible figure of merit for the intended application [70].

3. Structural Configuration of Plasmonic Based Refractive Index Sensor:

One of the most captivating applications of Plasmonics lies in its ability to guide and manipulate light at dimensions impossible using traditional photonic methods. This section discusses plasmonic waveguides, outlining their design principles and mechanisms of operation [71]. The integration of plasmonic sensors with various resonators is explored in this section, as well as illuminating how the sensitivity of plasmonic resonances changes with different types of analytes for sensing.

3.1 Ring Resonator Based Plasmonic Sensor:

Ring resonator-based plasmonic sensors are preferred because of their compact size and easy installation with the primary waveguide [72]. These sensors are commonly used for label-free detection of analyte, such as bimolecular or chemicals, in various applications, including biological and environmental sensing. The ring-based sensor has multiple combinations such as square ring resonator, circular ring resonator, notch filter resonator, hexagonal-shaped ring resonator, etc. [73]. Ring-based plasmonic refractive index sensors can integrate multiple sensors on a single chip.

A SOI ring resonator based on a slot waveguide was proposed by Raj Singh et al. for use in bio-sensing. The typical level of sensitivity is 300nm/RIU [21]. To detect hemoglobin in blood samples, Azad et al. introduced the idea of a whispering gallery mode ring resonator [20]. The optimal sensitivity obtained using the finite element approach is 361.3 nm/ RIU with a quality factor 1143. The author demonstrated that the ring resonator's light-analyte interaction length segment is longer than other plasmonic-based optical devices [20]. The ring resonator's effective interaction length is given by [20]:

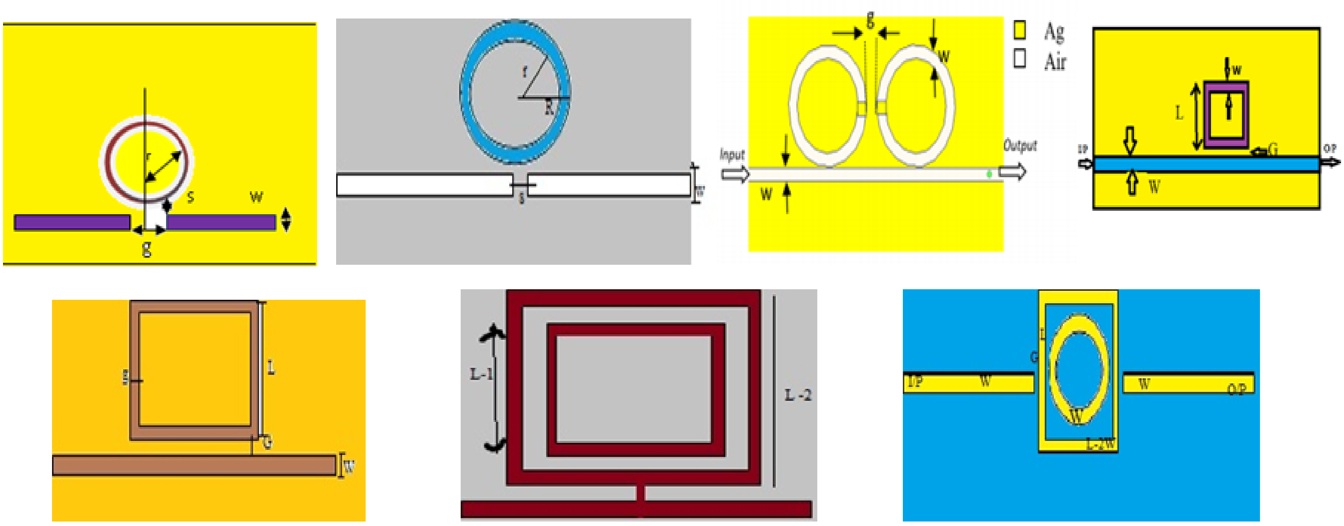

FIG. 2 DIFFERENT CONFIGURATION OF RING RESONATOR [13] [14] [15] [17] [19] [20] [21]

$$L_{eff} = \frac{\lambda_{res}}{\Delta\lambda} \quad (5)$$

Where λ_{res} is the resonance wavelength in µm, and L_{eff} is the effective interaction length between the ring resonator and the primary waveguide. Due to the narrow bandwidth in ring resonance, a higher quality factor value can be obtained. However, the sensitivity is entirely compromised with these optimized parameters. D. Chauhan et. Al. presented an MDM waveguide coupled with a ring resonator, and the uniqueness of this sensor is that it can detect the high range of refractive index of analytes [13]. This sensor has a maximum sensitivity of 1200 nm/ RIU. The author also showed that if there is no phase change in light traveling in the ring waveguide [13].

The author demonstrated how an increase in the number of rings directly impacted the sensor's sensitivity [13]. However, the sensor's sensitivity is unchanged by modifying the spacing between these two MIM waveguides. Using a double concentric square ring resonator with one stub, Asgari et al. enhanced the sensitivity up to 1250 nm/ RIU [15]. The proposed sensor's sensitivity can be improved by 1275 nm/ RIU by increasing the no. of stubs 1 to 3 [15]. The application of this sensor to the near-infrared area of integrated circuits is particularly beneficial. A nano square ring connected with a MIM waveguide was studied by Butt et al. [18].

The maximal sensitivity attained by applying finite element approach techniques is 1320 nm/ RIU. Furthermore, the author also showed that the insertion loss lies between 7.83 to 10.83 db for w= 100 nm, and this loss can be minimized by optimizing the value of W and H. Jumat et al.[18] suggested using a MIM waveguide in conjunction with a rectangular and circular ring resonator, with a maximum sensitivity of 1965 nm/RIU. The author also contrasted sensitivity between a slit in the resonator and one without. The MIM waveguide and rectangular and circular ring resonators were combined, as proposed by Jumat et al., to produce the most excellent sensitivity of 3400 nm/ RIU. They stated that Q = 42.28 and the figure of merit is 36. Ag baffles add mode and boost sensitivity [14].

3.2 Stub and Waveguide based plasmonic sensor:

Waveguide-based plasmonic sensors are vital in integrating many devices, such as multiplexers, switch, filter, directional couplers, etc. In Metal- Insulator-Metal, the insulator is sandwiched between two metal layers and possesses high propagation losses but supports sub-wavelength confinement of signal, whereas in Insulator-Metal- Insulator scheme, metal is sandwiched between two metal layers and maintains low propagation loss [74]. Waveguide-based plasmonic refractive index sensors offer several advantages, such as high sensitivity, label-free detection, and the potential for miniaturization. They find applications in fields such as biomedical research (for detecting bimolecular interactions), environmental monitoring (for detecting pollutants), and industrial quality control (for chemical analysis) [75]. The longitudinal and transverse dielectric constant in MIM and IMI waveguide can be shown as:

$$\xi_{11} = \xi_m(\lambda)f + \xi_d(1\text{-f}) \quad (6)$$

$$\xi_{12} = \frac{1}{\left(\frac{f}{\xi_m(\lambda)} + \frac{(1-f)}{\xi_d}\right)} \quad (7)$$

Where, ξ_d is the dielectric constant of the dielectric layer and $\xi m(\lambda)$ is the dielectric constant of the metal. F stands for the metal filling factor per unit volume.

Turduev et al. presented a waveguide with a T-shaped slot with an average sensitivity value of 1040 nm/ RIU and an overall sensitivity of 500 nm/ RIU; however, the total sensitivity can be enhanced due to structural configuration [34].

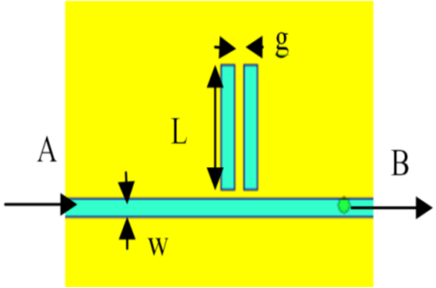

FIG 3. COUPLED STUB RESONATORS BASED MIM PLASMONIC SENSOR [76]

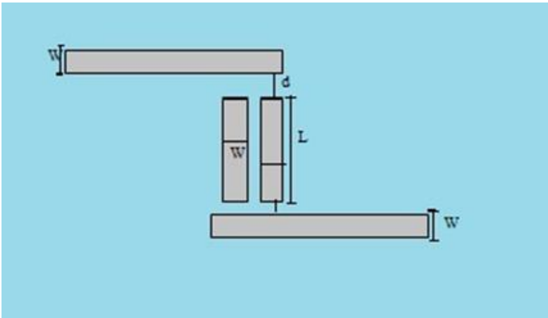

FIG. 4 COMBINATION OF TWO STUBS RESONATOR WITH TWO MIM WAVEGUIDE BASED PLASMONIC SENSOR [29]

The combination of two stubs and a MIM waveguide also demonstrated and sensed the refractive index of the liquid or gas in the MIM waveguide. The suggested sensor's maximum sensitivity of 1060 nm/ RIU is attained with FOM 176.7 [24]. The author also suggested using an elliptical ring resonator and MIM waveguide design to increase sensitivity. The maximum sensitivity measured is 1100nm/RIU with FOM=224. For applications based on sensing, a combination of MIM waveguide and two stub resonators is also suggested, and this combination yields a maximum sensitivity of 1145 nm/ RIU[24]. The author also contrasts the results with a single and double resonator. Hassan et al. designed the dual rectangular silver slot that is

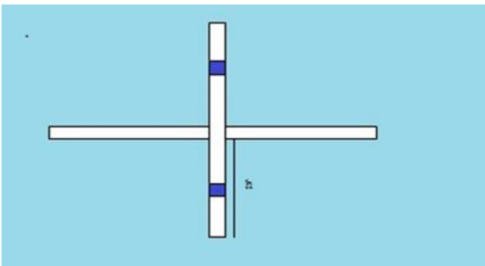

FIG. 5 COMBINATION OF TWO WAVEGUIDE WITH ASYMMETRY IN TWO SIDES [38].

perpendicularly connected with two horizontal dielectric-metal-dielectric waveguides.

The suggested sensor has a resolution of 8.72x 10-7 RIU and a maximum sensitivity of 1228.67 nm/ RIU. A liquid-core waveguide micro-fluidic optical sensor with a sensitivity of more than 1280 nm/RIU was proposed by Wu et al. in 2019[36]. Rakshani et al. suggested combining a racecourse resonator and two plasmonic MIM waveguides to achieve a maximum sensitivity of 4650 nm/RIU. Increasing the lateral length of the resonator can increase sensitivity [32].

3.3 Photonic Crystal Fiber Based Plasmonic Sensor:

Photonic crystal fibers are specialty optical fibers with a periodic arrangement of air holes that create a photonic bandgap, allowing for precise light propagation and confinement control. Internal periodic capillaries encircle the core of a photonic crystal fiber[76]. The working principle of A multi-core PCF-SPR biosensor using a gold layer as the plasmonic material was proposed by Kaul et al. in 2018. According to him, the amplitude sensitivity is 4470 db/RIU and the spectral sensitivity is 4000 nm/RIU, which is superior to the traditional and basic PCF construction [35]. Mollah et al. introduce a photonic crystal fiber-based dual polarization plasmonic refractive index sensor with an enhanced peak wavelength sensitivity of 12,000 nm/ RIU. And 2044/ RIU [40] has the maximum amplitude sensitivity. The author also demonstrated that for the analyte refractive index fluctuation of 1.37–1.41, the greatest sensor resolution is 8.33x 10^{-6} RIU [40]. To increase the connection between core mode and SPP mode and hence the sensitivity, Haider et al. studied a scaled-down method. The highest wavelength sensitivity in the x mode is30,000 nm/ RIU, and in the y mode is 22,000 nm/ RIU [23].

In 2020, Sharma et. al proposed a PCF filled with toluene and obtained the flat dispersion with low loss so this work can be further studied as a plasmonic based refractive index sensor.

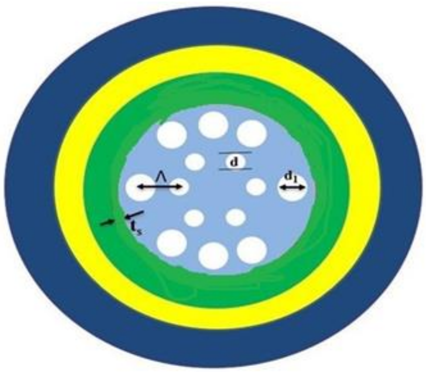

FIG. 6 CROSS SECTIONAL VIEW OF THE PROPOSED HEXAGONAL LATTICE PCF SENSOR [75]

3.4 Cavity Based Plasmonic Sensor:

Cavity-based refractive index sensors represent a frontier in plasmonic research, offering new opportunities for susceptible and localized measurements. The working principle of a cavity-based plasmonic refractive index sensor involves confining the plasmonic field within a cavity structure, often created using nanostructures or microstructures. The plasmonic cavity can consist of two closely spaced metallic surfaces, such as metal films or nano-particles, which support surface Plasmon resonances [77]. When the refractive index of the surrounding medium changes, it affects the resonance conditions of the plasmonic cavity, which leads to shifts in the resonant frequency or wavelength [78]. These shifts can be monitored and quantified to determine the changes in the refractive index. The cavity resonator enhances the interaction between the Plasmon and the external medium. Creating precise and reproducible cavity structures that support plasmonic resonances can be challenging in cavity based refractive index sensor [55]. The resonance properties of the plasmonic cavity can often be tuned by adjusting the dimensions or materials of the cavity, allowing for optimization of sensor performance [56]. Optical cavities strongly interact with light-analyte due to less volume and a high Q factor. So due to solid confinement, the cavity based plasmonic structure can be implemented in applying nonlinear optics, bio-sensing, chemical sensing etc [57].

Kwan et al proposed employing a double metal layer to create a disc cavity for MIM plasmonics. The maximal sensitivity can be increased to 1160 nm/ RIU [58] by adjusting the cavity parameters. A metal-insulator-metal waveguide with a side coupled disc cavity was proposed by Huang et al. in 2017 [59]. He offers a linear relationship between the resonant wavelength and the disc cavity's refractive index [60]. The maximum sensitivity value is 1320 nm/ RIU by optimizing different parameters [57]. Hasan et. al proposed a MIM waveguide based refractive index sensor coupled with three rectangular cavities and increase the sensitivity to 7564 nm/ RIU[61].

3.5 Silicon Based Plasmonic Sensor:

Silicon-based plasmonic sensors offer several advantages due to the compatibility of silicon with existing semiconductor fabrication technologies, making them well-suited for integration with electronics and photonics systems[64]. Silicon-based sensors can be fabricated at the micro- and nanoscale, enabling the development of compact and susceptible sensors. Silicon has a high refractive index, so it can support plasmonic resonances at longer wavelengths than noble metals like gold and silver. This is advantageous for specific applications [65]. However, silicon supports plasmonic resonances at longer wavelengths; it may not be suitable for applications that require plasmonic effects in the visible or near-infrared range [66]. The MIR band is used in several applications in the fields of environmental, commercial, and medical monitoring [67]. Due to silicon's limited material properties, tuning plasmonic resonances in silicon structures can be more challenging than noble metals. Silicon-based plasmonic sensors can be integrated with silicon waveguides, allowing for efficient coupling and manipulation of light signals [69].

Shahmat et al. proposed a waveguide with three rectangular nanocavities and a semiconductor-metal-semiconductor bus waveguide [62]. A temperature sensor's transmission and absorption characteristics are examined using the FDTD method. The highest sensitivity of this temperature sensor is 1.48 nm/° C [62]. Dwivedi et al. presented a metal under-clad ridge waveguide, a dispersion turning point in the dual mode region. The refractive index sensitivity of the interferometric sensor was 90 m/ RIU, and the greatest FOM was 4500[63]. Butt et al. depicted a metal-assisted waveguide with a thin layer of Sio2. The proposed sensor attains a maximum sensitivity of 300nm/ RIU [12]. As fabrication methods improve and new designs are developed, these sensors hold promise for a wide range of applications in both fundamental research and practical technology development.

3.6 Array Based Plasmonic Sensor:

Array-based plasmonic structure used high sensitivity. The array structure can be implemented on a high-density planar and compact design [70]. These sensors combine plasmonic principles with the concept of arrays, enabling multiplexed and parallel detection of multiple analytes. Array-based plasmonic sensors are particularly useful in high-throughput applications and for simultaneous monitoring of various interactions. The working principle of an array-based plasmonic refractive index sensor is similar to that of a single plasmonic sensor. Each element in the array consists of a plasmonic nanostructure (such as a nanoparticle or nanowire) designed to support localized surface plasmon resonances. When the refractive index of the surrounding medium changes, it affects the plasmon resonance conditions of each nanostructure. Ongoing research focuses on improving these sensors' sensitivity, specificity, and reliability while addressing challenges associated with array design, fabrication, and data analysis [71].

Singh et al. were the fiber optic surface Plasmon resonance sensor's representatives. Ten round gold nano-rods are arranged in a grid to form the sensor. Its sensor's maximum sensitivity is 2200 nm/ RIU, and its circular gold nano-rod radius is 60 nm [66]. Rakshani et al. proposed a two MIM waveguide with a silver nano-rods array built in a square resonator that attains its maximum sensitivity as 2320 nm/ RIU [68].

TABLE I

COMPARISON OF DIFFERENT REFRACTIVE INDEX SENSOR ON THE BASIS OF SENSOR PARAMETER AND TOPOLOGIES.

S. N.	*Design*	*Description*	*Parameters*	*References*
1.	MIM micro ring resonator with hybrid plasmonic waveguide.	Investigated and fabricated an Integral and optimized of HPWG and a MIM ring resonator cavity design.	S =800nm/RIU. FOM=37. Q=70.	[12]
2.	Fabry parrot structure like waveguide and micro ring resonator	A ring resonator construction using FANO resonance is used in a sub wavelength plasmonic liquid sensor.	S = 1200nm/RIU. Maximum Q= 62.6	[13]
3.	Two MIM waveguide	Sensor based on a combination of circular and rectangular resonators with silver baffles was proposed.	S= 3400 nm/RIU. FOM= 36. Q=42.28	[14]
4.	Twin concentric ring resonator linked with MIM waveguide.	Investigated a MIM waveguide-based double concentric square ring resonator with one to three stubs-based plasmonic refractive index sensors.	S =1250nm/RIU (one stub) and 1270 nm/RIU (three stub) FOM= 32.8 and 58.	[15]
5.	Whispering gallery mode ring resonator.	A ring resonator in whispering gallery mode is used to measure hemoglobin concentration.	S= 361.3 nm/RIU. Q= 1143.	[20]
6.	SPR sensor with a side core.	Investigated a surface plasmon resonance (SPR) sensor based on a photonic crystal fiber (PCF) with a silver core coated in analyte.	S= 23821 nm/refractive index unit (RIU) Resolution = 4.2 × 10−6 RIU Amplitude sensitivity= 819.3/ RIU.	[21]
7.	D-Shaped Photonic crystal fiber	Proposed a D-shaped Surface Plasmon Resonance (SPR) sensor built on Photonic Crystal Fiber (PCF), which is incredibly sensitive. The plasmonic substance is made out of gold.	S =26,000 nm/RIU Amplitude Sensitivity = 1680 RIU. FOM=1200, Resolution = 4.63 × 10−7 RIU.	[41]
8.	Periodic array of one D.	Investigated a one-dimensional periodic array of barium flint glass on a silicon nitride	S=2600 nm RIU-1. Q= 1500.	[30]

		(Si3N4) substrate coated with an active plasmonic material—a thin gold layer.		
9.	Silicon based hybrid Plasmonic waveguide.	A brand-new refractive index designed sub-wavelength grating silicon-based hybrid Plasmonic waveguide design was put forth.	S=1000 nm/RIU FOM=625. Q= 2569.8	[28]
10.	DMD waveguides or dielectric-metal-dielectric.	A double rectangular silver slot nano-scale refractive index sensor with two horizontal dielectric-metal-dielectric (DMD) waveguides connected perpendicularly was proposed.	S =1228.67 nm/RIU. Resolution = 8.72×10−7 RIU. Q=6.56.	[29]
11	Clad ridge waveguide (MUCRW)	An optimal dispersion turning point (DTP) in the dual mode area can be achieved by adjusting the core size of a metal under clad ridge waveguide (MUCRW).	S =90 µm/RIU. FOM =4500.	[63]
12.	Ring resonator	Two ring resonator designs based on slot and ridge waveguides have been proposed for monitoring glucose levels.	S =360nm/RIU Q=1316	[34]
13.	Square Ring resonator	Three Square Ring Resonator (SRR) designs based on Metal-Insulator-Metal (MIM) WG are suggested for gas sensing applications.	S= 1320. FOM= 16.7. Q=18.9	[18]
14.	Circular split ring resonator cavity with a rectangular baffle.	Investigated a MIM waveguide that has a split-ring resonator cavity that is round and has a rectangular baffle.	S=1114.3nm/RIU FOM=55.71	[14]
15.	Tooth cavity	MIM Waveguide with a tooth cavity was investigated in order to see the fano resonance in the transmission spectrum.	S = 1200 nm/RIU	[24]
16.	Racetrack	Hemoglobin detection	S = 4650nm/RIU	[32]

	resonator	via a 3-D MIM racecourse resonator was proposed.	

Conclusion and Future scope

In conclusion, this review paper comprehensively explores the captivating realm of plasmonic, from its fundamental principles to its transformative applications. By shedding light on the underlying physics, state-of-the-art technologies, and potential challenges, this paper aims to inspire researchers, engineers, and enthusiasts to dive into the world of plasmonics and contribute to its ongoing evolution at the forefront of nanoscience and technology. Plasmonic sensors have become potent instruments for label-free, in-the-moment detection, providing hitherto unheard-of sensitivity and specificity. The relationship between nanotechnology, optics, and material science has been demonstrated through developing these devices from their original concepts to their various applications. This review synthesizes the progress made in this dynamic field to provide academics, scientists, and professionals with a complete understanding of the development of plasmonic sensors and their prospective impact on different industries. This review is very beneficial for the beginner in the field of research to get the essential key points in the plasmonics domain. This manuscript elaborates on the significance and advantages of plasmonics-based refractive index sensors. A brief discussion about the sensor's parameters depending on different analyte ranges, different operating frequencies, the combination of the resonator with MIM waveguide, and suitable plasmonic material for sensing the other analyte has been carried out.

While plasmonics holds tremendous promise, it also faces significant challenges. This review critically evaluates limitations such as plasmonic losses, scalability of fabrication techniques, and integration with existing technologies. Furthermore, the paper speculates on the future directions of plasmonic research, envisioning advancements in active plasmonics, quantum plasmonics, and the fusion of plasmonics with other emerging fields.

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