

Original Article

Investigating Types of Plasmonic Sensors and their Applications

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Abstract: In this research, we will first introduce the science of plasmonics and then we will examine plasmonic sensors. us to make a suitable and better quality sensor by changing part of their structure than the previous sensors. Plasmonic sensors have a simple frame and high optical resolution and are able to transmit and guide plasmonic waves. Plasmonic sensors are widely used in the manufacture of military, industrial, medical and laboratory equipment. They also have basic applications in psychology and Cosmetic surgeries.

Keywords: Optics, Plasmonics, Plasmon surface polaritons, Insulation metal, Refractive Index Sensor Laser.

I. INTRODUCTION

Plasmonics is a large part of the science of nanophotonics and investigates how electromagnetic fields are confined in dimensions smaller than wavelength. Plasmonics describes the interaction processes between electromagnetic radiation and conducting electrons at a metal interface or in small metal nanostructures that will increase the near-field optical field with sub-wavelength dimensions. Research in this field explains how to create a distinct and unexpected behavior by applying discontinuities or sub-wavelength structure [1]. Plasmonic eliminates the size limitation in photonic circuits as well as the speed limitation in electronic circuits and as a result, it provides the possibility of achieving circuits with the speed of photonic circuits and nanometer dimensions of electronic circuits and it can be a bridge between electronics (with small dimensions, low speed and time delay of internal connections) and photonics (with high speed, large dimensions and diffraction limitation).

II. PLASMONIC DEVICES

The most important plasmonic components based on their structure are passive instruments (such as waveguides, couplers, filters, etc.) and active instruments (such as sensors, amplifiers, resonators, switches, modulators, etc.) that use the properties of plasmon wave propagation. Passive environments are isotropic and have only one refractive index and are unsuitable for switches and sensors, but active environments are anisotropic and the refractive index and wavelength can be changed by applying an external factor (Fig.1).

III. PLASMONIC SENSORS

Plasmonic sensor nanosystems are key and important parts of optical integrated circuits that must be developed. Plasmonic sensor is a device that detects the presence of the substance to be analyzed in the tested sample and measures it quantitatively [2-5]. The main function of a sensor is to identify and measure a physical, chemical or biological parameter. The sensor system consists of a power source, a converter, a data storage section, and a display and processor (Fig.2). The converter converts the input energy into an electrical signal. This signal is prepared for display by the display after being processed in different steps and calibrated in the memory section. Due to the special field distribution of resonances, optical sensors will be highly sensitive to changes in the refractive index of the environment. Also, the sensitivity of the optical sensor depends a lot on the material and structure of the sensor. Sensing is recognized as one of the best and most accurate applications for the evolution of plasmonic and photonic technology, and almost every new plasmonic or photonic structure is investigated to test the sensing capability. In order to use plasmonic and photonic sensors in industrial applications, an optical sensing technology map is absolutely necessary and vital, as is the design of a plasmonic refractive index sensor. Optical sensors are widely used to measure refractive index in chemical, biomedical and food industries. The design, analysis, and numerical evaluation of plasmonic sensors are done using arrays such as resonators and waveguides, and the purpose of this work is to reach acceptable and practical parameters in plasmonic sensors.



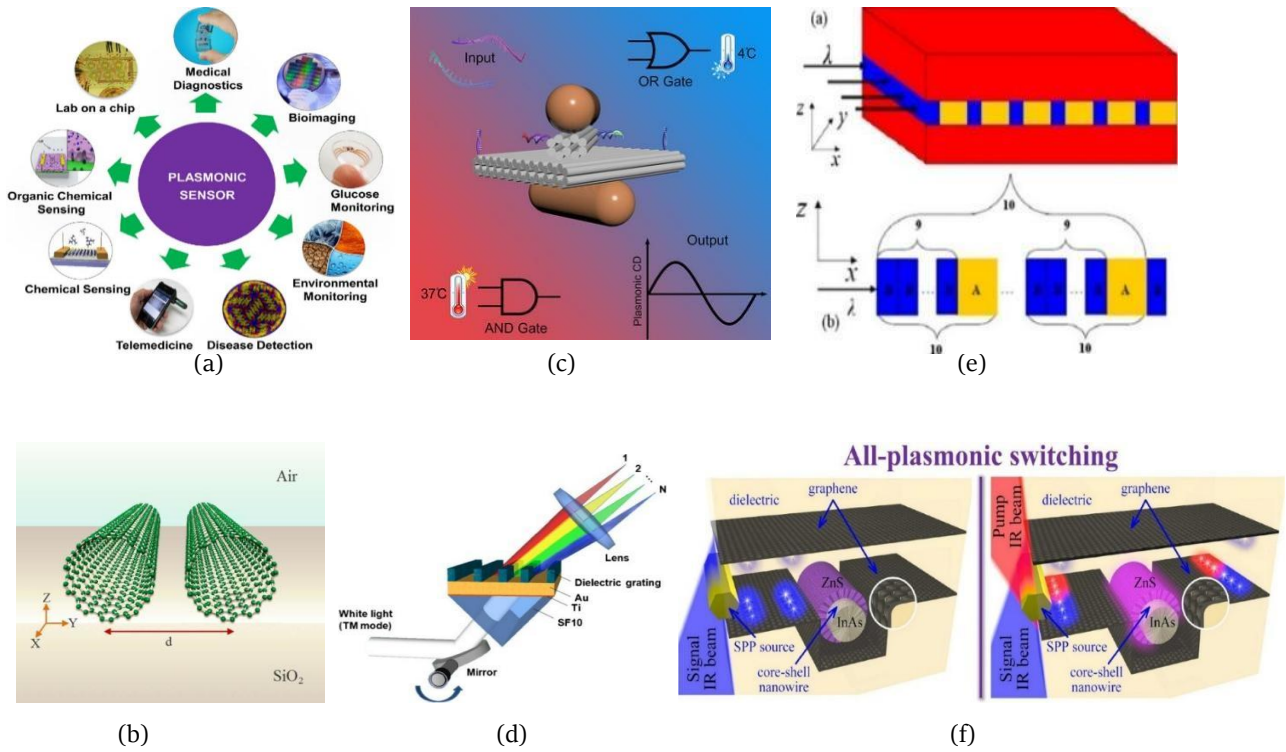


Figure 1: Plasmonic Devices: a. Plasmonic Sensor b. Plasmonic Coupler. c. Plasmonic Logic Gate. d. Plasmonic Wavelength Divider. e. Plasmonic Filter. f. Plasmonic Switch

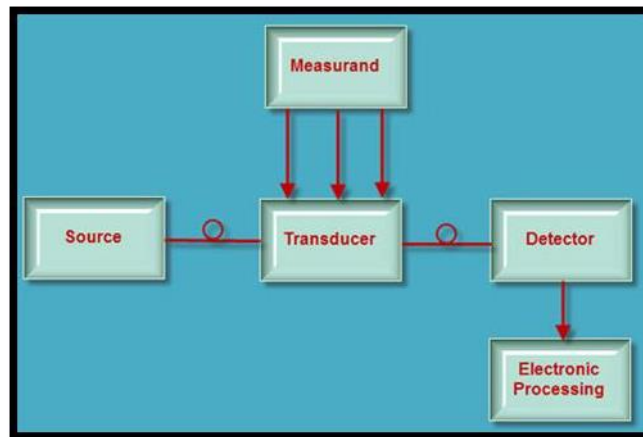


Figure 2: System Overview of a Plasmonic Sensor

IV. TYPES OF SENSORS

Optical refractive index sensors are divided into six categories based on plasmonic and photonic structures:

A. Metal-Based Propagating Plasmonic Eigenwave Structures:

These sensors are made by surface plasmon polariton (SPP). Surface plasmon polariton is a non-radiative electromagnetic surface wave that propagates parallel to the metal-dielectric interface. Since the wave is located at the boundary of the conductor and the external environment, these oscillations are very sensitive to any change in this boundary. The surface plasmon polariton emission at the metal-dielectric interface has an emission constant β_{sp} , which is greater than the optical wave number in the dielectric ($k_0 n_d$), that is:

$$\beta_{sp} = k_0 \sqrt{\frac{\epsilon_m n_d^2}{\epsilon_m + n_d^2}} \quad (1)$$

Where k_0 is the free space wave number, n_d is the dielectric refraction coefficient and $\epsilon_m = \epsilon_{mr} + i\epsilon_{mi}$ is the permittivity of the metal. The surface plasmon polariton at the flat dielectric metal interface is not excited by direct illumination, so the excited light wave must have more momentum. According to Fig.3, the main methods of introducing this extra momentum include prism connection, network connection, waveguide connection and fiber connection [6-10]:

a) *Surface Plasmon Polariton Connected to the Prism:*

Prism coupling, which is the most common method for stimulating surface plasmon polariton, has two configurations: Kerchmann (Fig.1 a) and Otto (Fig.1 b). Both configurations consist of a prism with a high refractive index n_p , a thin metal layer and a dielectric layer (sensing medium) with a lower refractive index. An anomalous wave created by a polarized magnetic (TM) light penetrates through a metal layer of appropriate thickness at the interface of the prism layer and the metal, and upon phase matching, excites the surface plasmon polariton at the metal-dielectric interface. When the phase matching condition is met, the following equation is obtained:

$$k_0 n_p \sin \theta = \{\beta_{sp}\} = Re \left\{ k_0 \sqrt{\frac{\epsilon_m n_d^2}{\epsilon_m + n_d^2}} \right\} \quad (2)$$

θ is the angle of incidence. A change in the refractive index of the sensor structure causes a change in the phase matching conditions and As a result, it leads to a change in the spectral response of the structure (such as Connection angle, Connection wavelength, phase and intensity). The sensitivity of the refractive index by scanning the wavelength can be obtained using equation (2):

$$S_{RI}^{prism} = \frac{\epsilon_{mr}^2}{\frac{n_d^3}{2} \left| \frac{d\epsilon_{mr}}{d\lambda} \right| + (\epsilon_m + n_d^2) \epsilon_{mr} \frac{dn_p}{d\lambda} \frac{n_d}{n_p}} \quad (3)$$

This shows that there is a higher refractive index sensitivity at longer wavelengths, although due to the increase in FWHM [11,12].

B) *Surface Plasmon Polariton with Grating:*

Surface plasmon polariton sensors based on grid connection use the diffraction of light in a metal grid (Fig.3c). When the following coupling condition is met, the diffracted light waves will be coupled to the surface plasmon polariton:

$$k_0 n_p \sin \theta + m \frac{2\pi}{\Lambda} = \pm Re \left\{ \beta_{sp} \right\} \quad (4)$$

Here, θ is the angle of incidence, Λ is the diffraction grating period, and m is an integer indicating the diffraction order. The analytical expression of the refractive index sensitivity can be obtained from equation (4):

$$S_{RI}^{grating} = \frac{\frac{m\lambda}{n_d \Lambda} + \sqrt{\frac{\epsilon_{mr}}{\epsilon_{mr} + n_d^2}} \frac{n_d^2}{|\epsilon_{mr} + n_d^2|}}{\frac{m}{\Lambda} + \frac{n_d^3}{2\sqrt{\epsilon_{mr}} |\epsilon_{mr} + n_d^2|^{3/2}} \frac{d\epsilon_{mr}}{d\lambda}} \quad (5)$$

The sensitivity of $S_{RI}^{grating}$ increases with wavelength and has a weak dependence on diffraction order. By comparing Equations (3) and (5), we come to the conclusion that non-branched surface plasmon polariton refractive index sensors with wavelength monitoring show higher sensitivity than grating refractive index sensors. Surface plasmon polariton sensors with Kerchman or Otto configurations are bulky and because of the use of prisms, it will be difficult to integrate them. But an optical waveguide joint that is compact and robust and easily integrated with other optical, electronic, and fluid components can be a suitable alternative. According to Fig.3d, the guided light propagates in the waveguide and penetrates through the metal strip. Finally, the surface plasmon polariton is excited at the interface between the metal and the underlying layer. Here, the coupling of the light with the surface plasmon polariton is similar to the Kerchmann configuration.

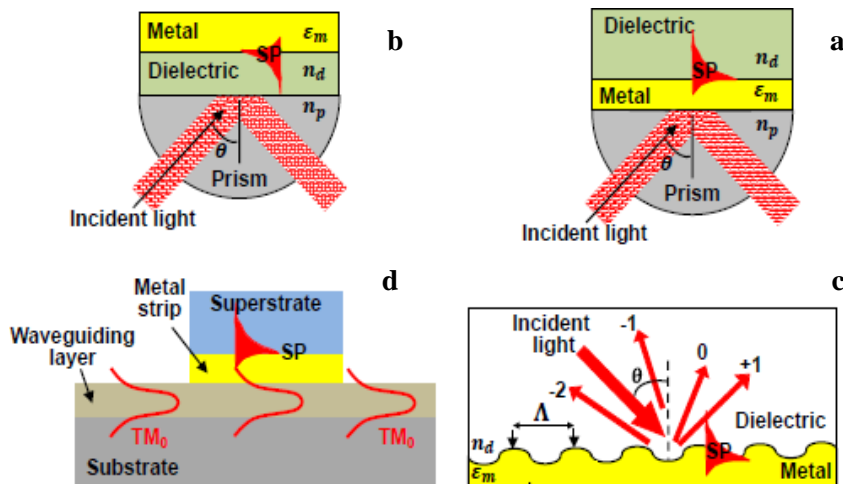


Figure 3: Schematics of Excited Surface Plasmon Polaritons (SPP). A. Kretschmann Configuration. B. Otto Configuration. C. Metal Mesh Configuration. D. Optical Waveguide Configuration [7].

C) Surface Plasmon Polariton Coupled with Fiber:

Optical fiber, as the most advanced waveguide technology, ensures the success of fiber-based surface plasmon polariton sensors (Fig.4). A surface plasmon polariton coupled to a fiber is similar to a prism pair where the fiber core acts as a prism in the Kretschmann configuration. Optical fiber surface plasmon polariton sensors have many advantages over bulk prism-based sensors, such as low cost, small footprint, and remote sensing capabilities. In an optical fiber waveguide, light is strongly confined in the fiber core through total internal reflection at the interfaces between the fiber core and the cladding, which prevents light from contacting the surrounding medium.

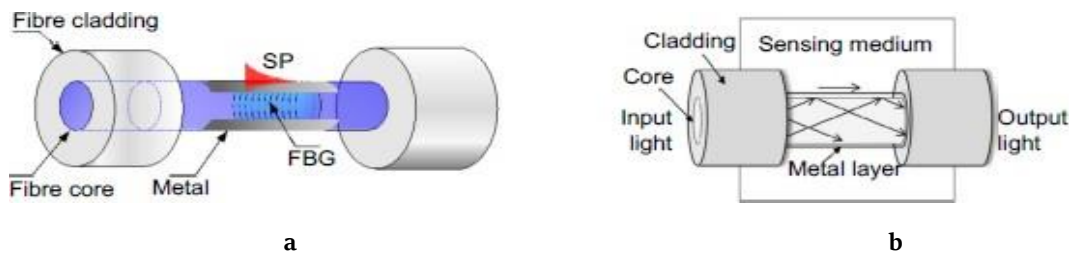


Figure 4: Schematic of Optical Fiber Coupled Surface Plasmon Polariton Sensors with Different Configurations. a) Fiber Modified with Geometry and Without Coating. a) Bragg Fiber Grating [13]

B. Localized Plasmonic Special Wave Structures Based on Metal:

The second type of optical refractive index sensor is metal-based plasmonic optical refractive index sensor, which is built on the special mode of localized plasmon, localized surface plasmon resonance. Localized surface plasmon resonance refers to collective electron charge fluctuations in a metal nanostructure, for example, metal nanoparticles (NPs). At the localized surface plasmon resonance wavelength, the amplified near field becomes localized in the region of metal nanoparticles and rapidly collapses in the dielectric medium. Therefore, the localized surface plasmon is also sensitive to changes in the dielectric environment. Localized surface plasmon is the result of collective but non-emissive fluctuations of electrons on the surface of metal nanostructures. The properties of local surface plasmon, such as resonance wavelength, depend on factors such as the shape, size, composition, and arrangement of the nanostructure, as well as the refractive index of the environment, which enables the construction of a refractive index sensor based on local surface plasmon [8, 9]:

a) Localized Surface Plasmon Based on Metal Nanoparticles:

In general, localized surface plasmon of metal nanoparticle structure has a lower sensitivity coefficient and form of competence than surface plasmon polariton refractive index sensors. The aspect ratio R is defined as $R = L/d$ (Fig.5) [14]. It is also found that the refractive index sensitivity depends on the plasmonic resonance wavelength and there is a linear relationship between the sensitivity of the refractive index and the resonance wavelength but the sensitivity of the refractive index to other parameters of metal nanoparticles, such as shape, size, composition and cross-sectional area, has a weak relative dependence.

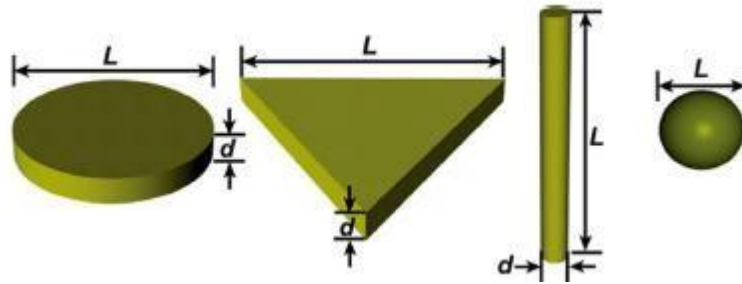


Figure 5: Schematic of Localized Surface Plasmon Sensors (LSPR) Based on Nanoparticles With Different Shapes Including Nanodisc, Nanoprism, Nanorod and Nanosphere [14]

b) Localized Surface Plasmon Based on Nanoslit (NH):

The plasmonic response of nanogaps in a dielectric medium is much more complicated than that of metal nanoparticles. The identified mechanisms include Bloch wave, localized surface plasmon and Fano resonance. Compared with metal nanoparticle-based refractive index sensors, nanoslit-based refractive index sensors were found to have similar refractive index sensitivity but higher FOM.

C. Dielectric-Based Propagating Photonic Special Wave Structures:

This section examines three representative types of dielectric-based photonic propagating refractive index sensors, i.e., Bloch surface wave, fiber grating, and fiber interferometer.

a) Bloch Surface Wave:

This wave is a surface electromagnetic wave that propagates at the dielectric- dielectric interface, which is considered as an analogy to the surface plasmon polariton that forms at the dielectric-metal interface. Similar to the metal-based surface plasmon polariton, the Bloch surface wave can be excited by a Kirchmann configuration or lattice coupling [15-18]. Similar to the surface plasmon polariton, the electromagnetic field of a surface Bloch wave is strongly confined and increases significantly near the surface and decays exponentially in water (Fig.6).

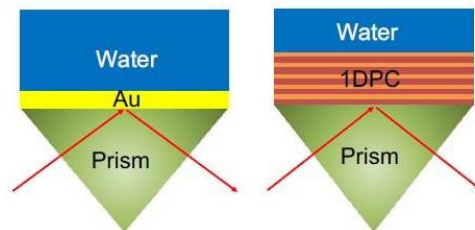


Figure 6: Schematic of Refractive Index Sensors Based on Bloch Surface Wave (BSW) (Gold-Based Surface Plasmon Polariton Sensor (Left) And Bloch Surface Wave (BSW) Sensor Based On One-Dimensional Photonic Crystal (Right)) [19].

Dielectric-based Bloch surface waves should have the following advantages over metal-based surface plasmon polaritons:

- Low losses as a result of faster amplification due to the low extinction coefficient of dielectrics.
- One-dimensional crystal photonics can be designed to support both TE and TM transverse polarizations of surface Bloch waves, while polaritons of surface plasmons are polarized only by the TM mode.
- Proper selection of material and thickness of one-dimensional crystal photonic layers provides more freedom to adjust Bloch surface wave resonance characteristics.
- Bloch surface wave sensors based on one-dimensional crystal photonics are chemically stronger because the dielectric layers are inert to the chemicals in the environment. The Bloch surface wave based sensor performance is also robust against thickness perturbation.

b) Fiber Grating:

Bragg fiber grating occurs through the coupling between the main core mode and its opposite emission mode, which results in resonance at the Bragg resonance wavelength:

$$\lambda_{res}^{FBG} = 2 n_{core}^{eff} \Lambda \tag{6}$$

is the effective refractive index of the propagation mode in the fiber core, and changes in the refractive index of the medium cause changes in the effective refractive index n_{core}^{eff} and Bragg resonance wavelength. However, due to the limitation of propagation modes in the fiber core, the effective n_{core}^{eff} is hardly affected by the surrounding environment. Therefore, a natural fiber Bragg grating is inherently insensitive to external refractive index changes. In order to use the fiber Bragg grating in measuring the refractive index, some modifications (such as reducing the thickness of the fiber coating along the grating area) must be done (Fig.7). This causes the diffusion to interact with the surrounding environment and is affected by the refractive index of the environment [20-22].

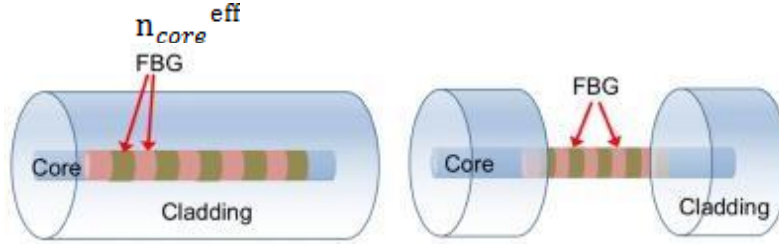


Figure 7: Standard (Left) and Etched (Right) Fiber Bragg Grating (FBG) Based Refractive Index Sensors

Now the fiber Bragg grating becomes a tilted fiber Bragg grating by a common modification (tilting the grating plates at an angle to the optical fiber axis). The phase matching conditions for the coupling between the core mode and the cladding mode in the tilted fiber Bragg grating can be written as follows:

$$K_R = K_{core} + K_G \tag{7}$$

K_R , K_{core} , and K_G are the wave vectors of the incident light, core mode, and grating, respectively, for the tilted fiber Bragg grating. Of course, this phase matching condition depends on the tilt angle, which according to Fig.8, when the tilt angle is less than 45 degrees, the forward core mode is connected with the backward emission cladding mode, which leads to an ambiguous radiation angle. When the tilt angle is greater than 45 degrees, the incident light is connected to the forward emission cover mode. When the tilt angle is equal to 45 degrees, the radiation angle becomes 90 degrees, and the phase-matched light radiates completely from the fiber instead of being confined and diffused.

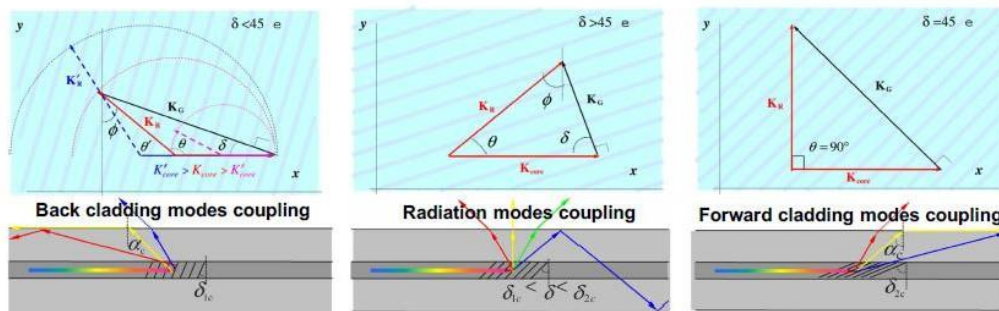


Figure 8: Phase Matching Conditions of a Tilted Fiber Bragg Grating (TFBG) for Three Modes

Unlike the unmodified fiber Bragg grating, the long period fiber grating is sensitive to changes in the refractive index of the medium. This inherent refractive index sensitivity of LPFGs results from the coupling between the core mode and the forward-propagating cladding modes with the phase matching condition for the cladding mode, m^{th} [23]:

$$\lambda_{res(m)}^{LPFG} = \frac{n_{core}^{eff} - n_{clad(m)}^{eff}}{n_{clad(m)}^{eff}} \Lambda \tag{8}$$

Here is the effective refractive index of the cladding mode, m^{th} , which depends on the refractive index of the medium. Therefore, the sensitivity can be optimized by properly choosing the order of the cladding mode (m) and grating period (Λ). The main limitation of long periodic fiber grating sensors lies in the range of its measurable refractive index, which is usually lower than the index of the cladding fiber [24].

c) *Fiber Interferometer:*

In an interferometer, light from a single source is split into two beams that travel through different optical paths and then combine to create interference. The resulting interference gives information about the difference in the optical path. To measure the refractive index, optical waveguide interferometer and optical fiber interferometer are the most widely used. Despite the different configurations, they all have a similar sensing principle, that is, the interaction between the analyte and the field at the end of an optical mode induces a phase shift, intensity changes, or a change in the resonance wavelength, and an interference pattern with the optical mode. It forms a reference. For consistency, we will focus on investigating refractive index interferometer sensors based on the resonance wavelength shift. We limit our discussion to fiber optic interferometers because most optical waveguide interferometers modulate phase shifts or intensity changes. The four refractive index sensors are conventional interferometer, Mach-Zehnder interferometer, Michelson interferometer, Fabry-Perot interferometer and Sagnac interferometer (Fig.9).

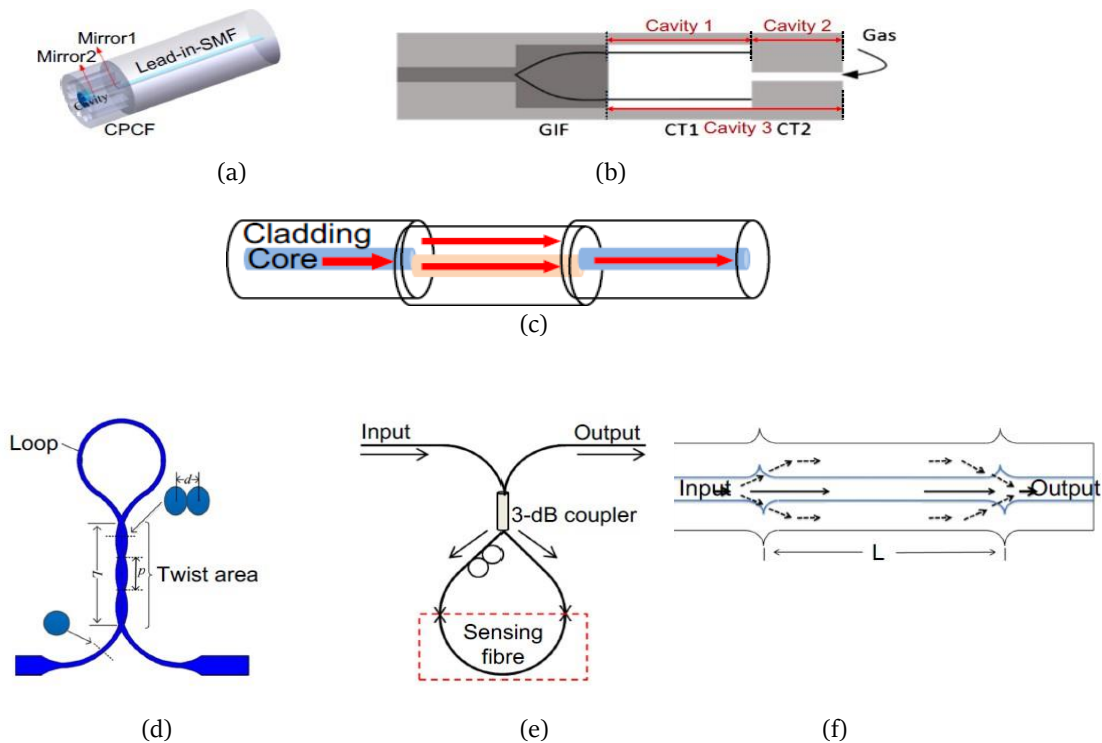


Figure 9: Refractive index sensors based on: A. Mach-Zehnder interferometer (MZI), b. Fabry-Perot Interferometer (FPI) (FPI hybrid sensor), c. Fabry-Perot Interferometer (FPI) (Based on Concave Core PCF), d. Sagnac Interferometer (SI) (Typical), e. Sagnac Interferometer (SI) (twisted microfiber), f. Michelson Interferometer (MI).

D. Local Photonic Special Wave Structures Based on Dielectric:

Two widely exploited local photonic eigenmode refractive index sensors are photonic crystal cavity sensors and whispering gallery mode resonator sensors (Fig.10). A photonic crystal is a periodic semiconductor structure with a photonic band gap in which the propagation of electromagnetic waves is strictly prohibited for a certain range of frequencies. A photonic crystal is created by creating defects in periodic structures that provide a way to localize the field (defect states) in the photonic band gap. The strongly confined field in the photonic crystal is sensitive to changes in the refractive index of the medium. This forms the basis of photonic crystal optical refractive index sensors [25]. Whispering gallery mode resonators, on the other hand, are dielectric structures where light is strongly confined in the resonator cavity through total internal reflection at the curved surface. Whispering gallery mode resonant sensor is a type of finite field sensor in which the unstable field of WGMs leaking into the surrounding medium is used to monitor the refractive index changes of the medium by changing the resonant wavelength [26].

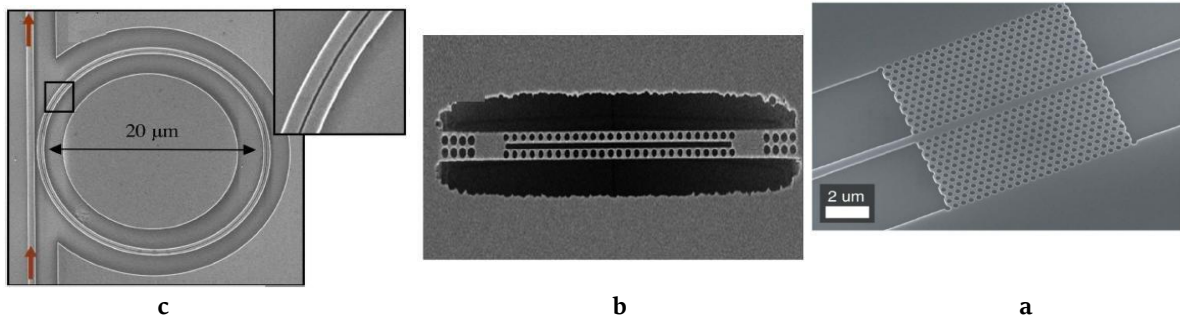


Figure 10: a. Photonic Crystal Cavity (PCC) Refractive Index Sensors (Photonic Crystal Waveguides (PCWs)). b. Refractive Index Sensors Based on Photonic Crystal Cavity (PCC) (Photonic Crystal Beam Nanocavities (PCNBC)). c. Refractive Index Sensors Based On Whispering Gallery Mode (WGM) Resonator (Silicon Grooved Micro-Ring Resonator)

D. Advanced Hybrid Structures:

Advanced hybrid refractive index sensors have also been investigated in recent years, which have shown excellent sensing performance. Here, the word "hybrid" refers to different levels of hybridization, such as:

a) Fano Resonance Sensors:

Fano resonance is the result of interference between a narrow discrete state and a broad spectral continuous state and has an asymmetric spectral line shape (Fig.11a). This unique spectral property is particularly useful for FOM amplification of refractive index sensors through narrow resonance.

b) Hybrid Emitting Localized Plasmonic Sensors:

In metal-based plasmonic refractive index sensors, we may have simultaneous excitation of SPP and LSPR emission, where the two may or may not be coupled to each other (Fig. 11b).

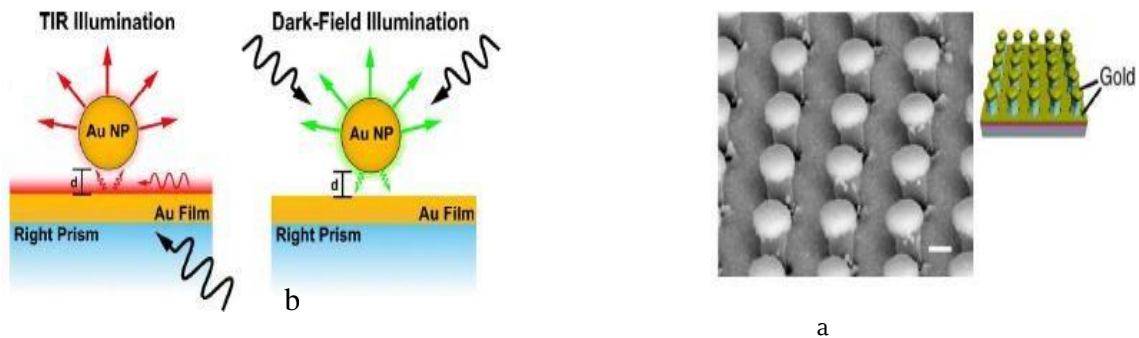


Figure 11: a. Fano resonance refractive index sensors. b. Combined propagating localized plasmonic refractive index sensors (total internal reflection (TIR) and dark field illumination schemes used to simultaneously excite propagating surface plasmons (PSPs) and localized surface plasmons (LSPs) in a single gold NP film structure)

Here, we review the propagating plasmonic (SPP) and localized (LSPR) sensors separately. Each of these two categories has its own unique power. Typically, propagating plasmonic eigenwaves have a relatively large active volume due to the deeper extension of plasmonic enhanced fields into the sensing medium. On the other hand, localized plasmonic eigenmodes tend to have highly concentrated fields with high enhancement. Only if the refractive index change occurs exactly at the places of increased field, i.e. the hot spot, the merit of localized plasmonic eigenmodes can be revealed. It should be emphasized that simultaneous stimulation does not mean connection. Upon resonance, the coupling of LSP and PSP sometimes produces hybridized plasmonic states such as Fano resonance [27-31].

c) Hybrid Photonic Plasmonic Sensors:

Using the concept of hybridization, we can also combine plasmonic and photonic effects to take advantage of their complementary strengths. Metal-based plasmonic refractive index sensors are usually more sensitive due to their surface wave nature. The electromagnetic fields of a plasmonic mode are concentrated on the metal surface, which can overlap with the active sensor volume. This results in a larger resonance shift and thus better refractive index sensitivity. On the other hand, dielectric-based photonic refractive index sensors have a larger FOM due to the lossless nature of the dielectric material, which will lead to sharper resonance. By combining both, optimal measurement performance can be achieved. We

call such sensors as hybrid plasmonic photonic refractive index sensors (Fig.12). A famous example can be the photonic plasmonic hybrid resonator of the whispering gallery mode [32].

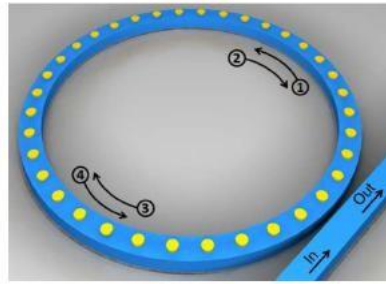


Figure 12: Photonic Plasmonic Hybrid Refractive Index Sensors (Decorated Silicon Metal Nanodisks On Insulator (SOI) Optical Ring Resonator (RR)).

E. Integrated Structures of Two-Dimensional Materials:

Here we cover two-dimensional material-based optical sensors for refractive index measurement. Namely integrated refractive index sensors of graphene and derivatives and refractive index sensors based on other 2D materials beyond the graphene family:

a) Graphene and its Derivatives:

Tunable and low-loss plasmons in graphene have been widely investigated in recent years, but the relatively inefficient coupling between light and graphene plasmons has limited its direct application in optics and photonics. By integrating graphene with conventional plasmonic materials, graphene-metal hybrid structures are enabled in the visible and near-infrared range with excellent tunability. Graphene can also be used to influence the optical response of plasmonic nanostructures, leading to active graphene-based plasmonics. Although graphene can be used as an alternative material in plasmonic sensors, most works still focus on graphene-metal composite structures (Fig.13) to measure the plasmonic refractive index at visible wavelengths [33-35].

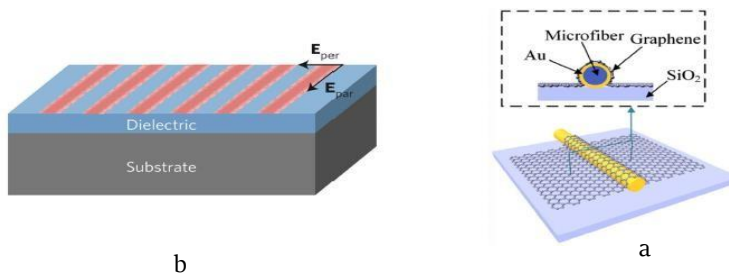


Figure 13: Plasmonic Refractive Index Sensors Integrated with Graphene: A. SPP Sensing System of Graphene Fiber / Gold b. LSPR Sensing System of Nanostrip Arrays).

Similarly, this graphene integration idea has also been applied to dielectric-based photonic refractive index sensors (fiber grating-based graphene refractive index sensors and fiber interferometers) (Fig. 14) [36,37].

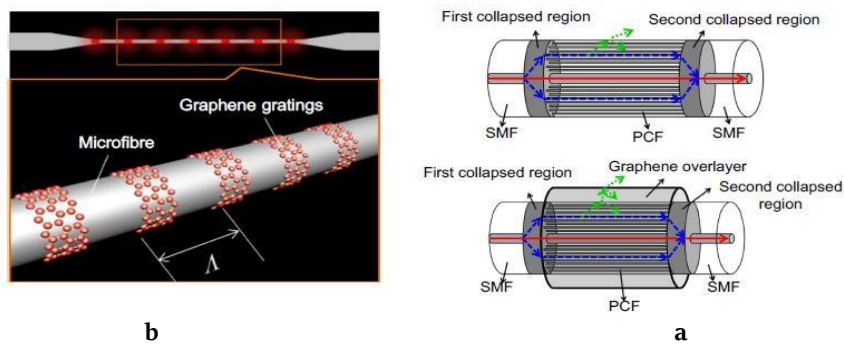


Figure 14: Photonic Refractive Index Sensors Integrated with Graphene Based On: a. Fiber interferometer (Mach-Zehnder Interferometers (MZI) Based on Photonic Crystal Fiber (PCF) with (top) and without (bottom) Deposition of Graphene Layer. b. Fiber Mesh (Graphene Bragg Grating on Microfiber)

b) Beyond Graphene:

The successful application of graphene and its derivatives in measuring the refractive index arouses the desire to discover other two-dimensional materials [38-43]. A two-dimensional material beyond graphene is two-dimensional layers of transition metal chalcogenides. This sensor has been used to monitor the changes in the absorbed power caused by the change in the refractive index of the environment in the refractive index range from 1 to 52.1 nm. In addition to two-dimensional layers of transition metal chalcogenides, a relatively new two-dimensional material, black phosphorus (BP), has recently been used for refractive index measurement. Using the heterogeneous structure of BP-graphene or BP-TMDCs can further increase the sensitivity of the refractive index (Fig.15).

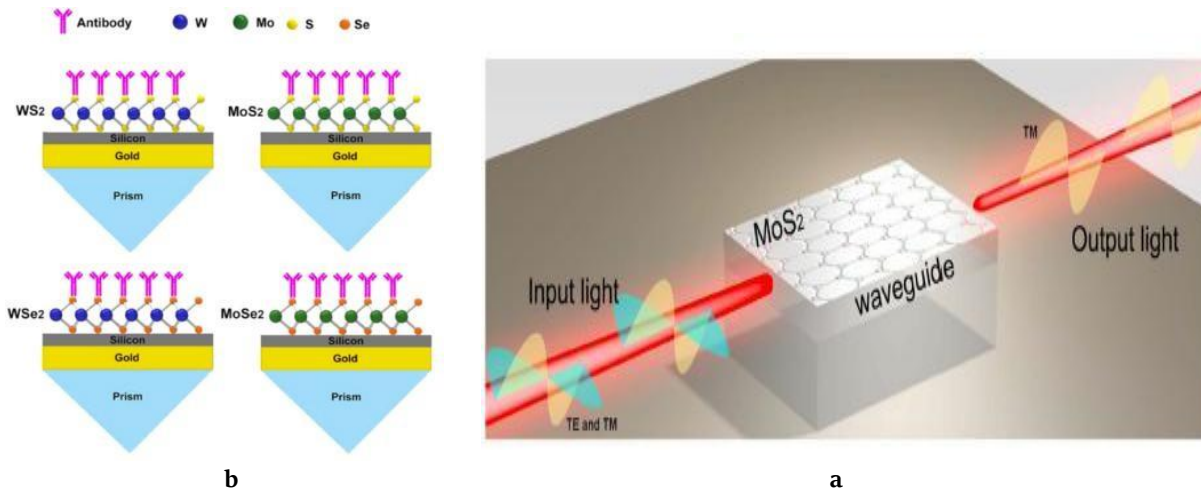


Figure 15: Other Sensors Based on Two-Dimensional Materials and Beyond Graphene: a. Polarization-Dependent Optical Absorption of MoS₂ for Ambient Refractive Index Measurement. b. Theoretical Study on Two-Dimensional Phase-Sensitive TMDC Plasmonic Biosensors

V. CONCLUSION

Optical sensors are widely used to measure refractive index in chemical, biomedical and food industries. Due to the special field distribution of resonances, optical sensors create high sensitivity to changes in the refractive index of the environment. The sensitivity of the optical sensor depends a lot on the material and structure of the sensor. Each new plasmonic or photonic structure is investigated to test the sensitivity capability. To push plasmonic and photonic sensors into industrial applications, an optical sensing technology roadmap is absolutely essential. The aim of this paper is to review a wide range of the most representative plasmonic and photonic sensors and to place them in a single map. The sensor performance of different structures is clearly shown. Future researchers can plot the capabilities of their new sensors on this technology map and measure their performance in this field.

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