

Current outlook and future potential of no-core fiber sensor technology based on plasmonic effect

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Abstract

This paper reviews presents a review of the current status and future prospects of plasmonic-effect-based No-Core Fiber (NCF) sensor technology. The discussion covers the basic principles of plasmonic effects, namely Surface Plasmon Resonance (SPR) and Localized Surface Plasmon Resonance (LSPR), the sensing mechanism of NCF, and the current status of plasmonic-based NCF sensor development. Plasmon-based NCF sensors have been widely applied in various measurement applications, with the majority of research focusing on refractive index sensors. Most studies still utilize SPR rather than LSPR, considering the technical challenges in controlling the size and shape of metal nanoparticles in LSPR. Nevertheless, LSPR provides design flexibility that enables precise tuning of nanostructure parameters to improve sensor sensitivity. Some potential development directions include optimizing sensor design to improve sensitivity and selectivity, developing more controllable and reproducible fabrication methods, and exploring new plasmonic materials. With the advancement of fabrication technology and characterization methods, it is expected that the technical challenges in developing plasmonic-based NCF sensors can be overcome. This advancement will facilitate broader applications across diverse fields, including chemistry, biosensing, and environmental monitoring.

Keywords: No-Core fiber, Plasmonic effect, Sensing technology

1. Introduction

In recent years, scientists have attempted to turn optical fibers, known for their exceptional ability to transfer data over long distances with extremely low loss, into sensors for various applications [1-3]. Compared to other sensing devices, optical fibers offer superior performances, including high sensitivity [4], compact size [5], salient selectivity [6], good stability [7], notable biocompatibility [8], and resistant to electromagnetic interference [9]. With their small size, high reliability, and excellent ability to operate in difficult environments, optical fiber sensors have advantages over non-optical sensors [10].

One promising type of optical fiber sensors is No-Core Fiber (NCF), comprising of a cladding and an outer protective layer in the absence of a core [11, 12]. NCF sensors show a more sensitive response to environmental changes compared to Multimode Fiber (MMF) or Single Mode Fiber (SMF) sensors. As there is no core in NCFs, light can interact with the environment as it travels through the fiber. In this sense, the external medium serves as the new cladding, and the NCF itself as the core [13]. When SMFs or MMFs used as sensors, the cladding layer needs to be modified to promote evanescent waves interact with the surrounding media [7]. This structural modification, for example tapering, can be achieved using several methods. This includes an etching process [9], which requires hazardous chemicals. Another method is the flame brush technique [14], which uses harmful gasses. Arc-discharge [15] also requires an expensive set-up. NCFs, on the other hand, do not require any structural modification as they already designed as sensors. This advantage make NCFs as an alternative for sensing applications in various fields, including for detection of temperature [16], [17], refractive index [18-20], biomolecules [21, 22] pressure [23], strain [24], moisture [25], and magnetic field [26, 27].

To improve the sensitivity of optical fiber sensors, scientists have been induced an optical phenomenon called the plasmonic effects, i.e., Surface Plasmon Resonance (SPR) and Localized Surface Plasmon Resonance (LSPR) into the optical fibers. These optical effects occur when light, particularly its electric field, interacts with the free electrons in metal [28], and the resulting SPR- and LSPR-based optical fiber sensors are considered more promising than conventional optical fiber sensors. In SPR, the evanescent wave in the metal-dielectric interface is in resonance with the surface electrons in metal. This process occurs when the metal is surrounded by a dielectric material. When light hits the metal surface, the electrons on the surface vibrate together. These shared electron vibrations are called surface plasmons [29, 30]. On the other hand, LSPR typically pertains to metallic nanoparticles, where the free electrons on the surface of nanostructure metals vibrate in the same frequency with the electric field of the incoming light.

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In conventional plasmonic-activated optical fiber sensors, part of the optical fiber coating is removed to promote more evanescent fields excite plasmonic effects in the metal or nanoparticles coating on the fiber surface. This method often involves various special treatments, including chemical etching [9], flame brush technique [14], or arc-discharge [15], as mentioned in the previous paragraph. Unfortunately, these modifications have serious drawbacks, especially fragility and reduced mode coupling efficiency [29, 31]. To overcome these challenges, NCFs have been adopted as a promising alternative for their ability to sensitively detect biochemical or physical changes, for example refractive index [15, 17, 18] and humidity [25]. In this sense, the integration of plasmonic effect and NCF offers a promising approach in the development of optical fiber sensing technology [31, 32].

There have been many review articles on optical fiber sensors. Most of the previous reviews discussed plasmonic effect-based optical fiber sensors in general, including aspects of working principles, structures, and various applications [29, 33, 34]. The use of different fiber types with different geometrical structures, including U-type, D-type, and Ω -type, has been reviewed [35]. Reviews were reported focusing on the principles and applications of SMF [36] and MMF [37] for sensing. However, no reviews have been reported on the development of plasmonic effect-based NCF sensors. NCF sensors play a significant role as they eliminate the need for fiber structural modification. Therefore, this review paper focuses on an in-depth study of plasmonic effect-based NCF sensors. This focus is essential to better understand the potential and applications of plasmonic effect-based NCF sensors. Herein, the fundamental principles and current outlook of the plasmonic-activated NCF sensors are discussed.

2. Activation of plasmonic effect in optical fiber sensors

2.1 Surface Plasmon Resonance (SPR)

SPR occurs as an optical effect when free electrons at the interface of a metal and a dielectric medium interact with polarized light. This interaction is particularly noticeable with *p*-polarized light striking metals containing free electrons, such as Au and Ag [38]. When *p*-polarized light hits a metal-dielectric interface, some of the energy from the light generate electromagnetic waves that propagate along the surface. These waves are called evanescent waves, having unique characteristics of a certain propagation constant and energy. At the same time, free electrons on the metal surface can oscillate collectively, forming what is referred to as a surface plasmon wave [39]. Resonance will occur when the characteristics of the evanescent wave match the characteristics of the surface plasmon wave. When this resonance occurs, the energy from the light does not just pass by, but most of the energy transfers to the plasmons on the metal surface. As a result, the metal surface absorbs the light energy very strongly. This absorption of energy causes the intensity of the reflected or transmitted light to decrease drastically. The intensity that decreases at a certain wavelength is called the resonance wavelength. Resonance occurs when the evanescent wave propagation constant (k_{ev}) is equal to the propagation constant of the surface plasmon wave (k_{sp}) [34, 40]:

$$k_{ev} = k_{sp} \quad (1)$$

$$\frac{2\pi}{\lambda} n_c \sin \theta = \frac{2\pi}{\lambda} \sqrt{\frac{\epsilon_{mr} n_s^2}{\epsilon_{mr} + n_s^2}} \quad (2)$$

where n_s is the refractive index of the dielectric sensing region, θ is the beam angle of incidence light wave, n_c is the refractive index of the optical fiber core, and parameter ϵ_{mr} is the real component of the metal's dielectric constant. In the SPR phenomenon, resonant plasmons can propagate through the metal film due to its size being considerably larger than the wavelength of light. The illustration of the SPR formation process over the metal film coating the optical fiber core in the sensing area is shown in Figure 1.

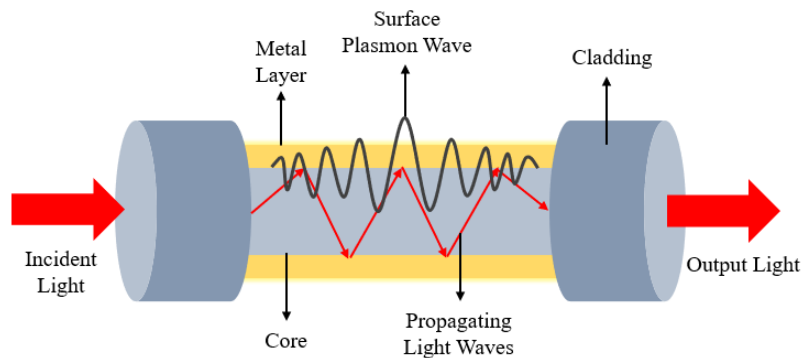


Figure 1 Schematic diagram of SPR phenomenon in optical fiber.

In many studies, the SPR effect is often utilized to improve sensor's sensitivity. One of its most common applications is to detect refractive index. When there is a small change in the refractive index near a metal surface, the resonant wavelength will shift. This shift can be seen by observing the change in the lowest point of the light absorption graph, enabling precise detection of the external refractive index. This ability of SPR to detect very small changes makes the NCF sensor more sensitive. Sensitivity is a key measure of how well a sensor performs. The sensitivity level of the sensor is calculated by comparing how much the resonant wavelength shifts against the measured refractive index change [41, 42]:

$$S_n = \frac{\Delta\lambda_{\text{peak}}}{\Delta n} \left[\frac{\text{nm}}{\text{RIU}} \right] \quad (3)$$

2.2 Localized Surface Plasmon Resonance (LSPR)

When light interacts with the electrons of conductive nanoparticles, it induces a photonic phenomenon known as LSPR effect. This interaction represents a fundamental process in the field of photonics [43]. The incident light's electric field induces collective oscillations of free electrons within the nanoparticles' conduction band. These oscillations occur only in the nanostructure metal layer, unlike SPR which can propagate. When the incoming light's frequency and wave direction coincide with the collective oscillations of free electrons in the metal nanoparticles, LSPR takes place [29]. In this scenario, active plasmonic materials with sizes smaller than that of the wavelength of light produce confined electron oscillations in metal nanoparticles. The LSPR effect is shown in Figure 2. Noble metal nanomaterials such as gold nanoparticles (AuNPs) and silver nanoparticles (AgNPs) are able to absorb photon energy from incident light. Noble metal nanomaterials such as gold nanoparticles (AuNPs) and silver nanoparticles (AgNPs) can absorb photon energy from incident light. This absorption contributes to strong optical extinction and enhances the local electromagnetic field around the nanoparticles. The wavelength corresponding to the maximum light absorption is referred to as the resonance wavelength. The number of plasmonic peaks depends on the shape and size of the metallic nanostructures [44].

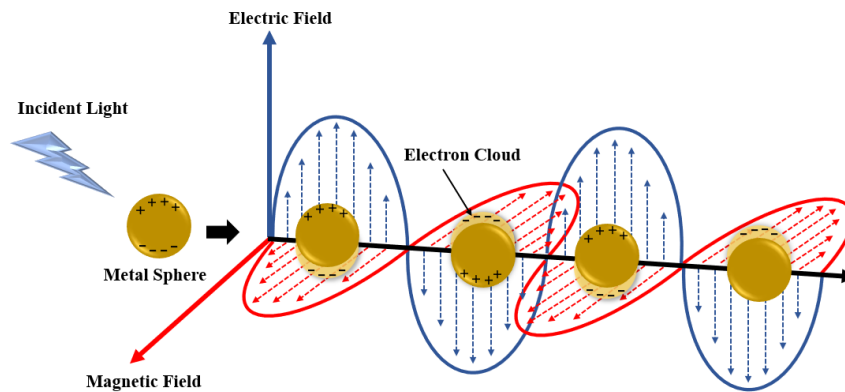


Figure 2 Schematic diagram of the LSPR phenomenon.

The interaction between LSPR and the surrounding media can be explained using the Drude model [29, 45, 46]. This describes the dielectric function of plasmonic materials, as follows:

$$\varepsilon_r = 1 - \frac{\omega_p^2}{\omega^2 + \gamma^2} \quad (4)$$

where ε_r is the real part of the complex dielectric function of the plasmonic material's (ε), ω represents the radiation angular frequency, ω_p represents the plasmonic frequency, and γ denotes the bulk metal damping parameter. Since γ is much smaller than ω_p in the infra-red and visible regions, Eq. 4 can be simplified to:

$$\varepsilon_r = 1 - \frac{\omega_p^2}{\omega^2} \quad (5)$$

When the wavelength of light is significantly larger than the particle size, the polarizability (α) can be determined by:

$$\alpha = 3\varepsilon_0 V \frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m} \quad (6)$$

where ε_0 represents the permittivity of the vacuum, V donates the volume of the nanoparticle, and ε_m is the dielectric constant of the surrounding medium. When the probability reaches a maximum, plasmon resonance occurs. As a result, $\varepsilon_r = -2\varepsilon_m$ becomes the resonance condition.

Considering the resonance condition in Eq. 5, the peak frequency of LSPR, $\omega_{\max}$ can be obtained as:

$$\omega_{\max} = \frac{\omega_p}{\sqrt{2\varepsilon_m + 1}} \quad (7)$$

taking $\lambda = 2\pi c/\omega$ and $\varepsilon_m = n_m^2$, Eq. 7 becomes

$$\lambda_{\max} = \lambda_p \sqrt{2n_m^2 + 1} \quad (8)$$

where λ_p is the wavelength that corresponds to the plasma frequency of metal nanoparticles and $\lambda_{\max}$ is the maximum LSPR wavelength. Eq. 8 shows a linear correlation between the maximum wavelength of the LSPR and the refractive index of the surrounding medium. Furthermore, Eq. 9 can be used to determine the sensitivity (S) of the LSPR sensor, which is the magnitude of the wavelength shift per refractive index unit.

$$S = \frac{\Delta\lambda}{\Delta n} \left[\frac{\text{nm}}{\text{RIU}} \right] \quad (9)$$

Several variables influence the sensitivity of LSPR optical fiber sensors, including the density, dimensions, geometry, and material composition of nanoparticles. By optimizing the geometry, dimensions, and material composition of metallic nanostructures, researchers can enhance the sensitivity, resolution, and signal-to-noise ratio of the LSPR-based optical fiber systems [47]. As a result, these sensors have been widely applied in various fields, such as biosensing and clinical diagnostics [35, 48].

In the manufacture of LSPR-based optical fiber sensors, a small portion of the middle/end cladding of the optical fiber is generally removed in such a way that metallic nanostructures can be coated on this surface-modified fiber region [33]. When light travels through the optical fiber core, a portion of the light's evanescent field will interact with the metallic nanostructures [35]. The light-matter interaction between the evanescent field and the metal nanostructures manifests in the occurrence of LSPR effect [3]. Under specific resonance conditions, a fraction of the spectral range of light is absorbed by the metallic nanostructures. This phenomenon can be detected by the occurrence of plasmonic peaks in the absorption/reflection spectrum of the light the the nanostructures-coated optical fiber [46, 49]. These absorption/reflection peaks can be used to trace the changes in refractive index, biological or chemical substances, or other physical changes near the sensing probes [50]. Thus, the LSPR-based optical fiber sensors are capable of detecting various types of analytes or environmental parameters by utilizing the evanescent waves and plasmonic effect.

3. Sensing mechanism of No-Core Fiber (NCF)

In traditional optical fibers, the core is enclosed by a lower-refractive-index cladding layer, enabling total internal reflection within the fiber [51]. However, in NCF, the entire cross-section of the fiber consists of one single material, usually pure silica, with a uniform refractive index throughout its cross-section [52]. In other words, there is no boundary between the core and the cladding, making evanescent waves are generated in the interface of the NCF and the surrounding medium. Therefore, the surrounding medium, acts as a cladding [9]. Unlike conventional optical fibers, NCF exhibits a distinct light propagation mechanism. Traditional fibers, such as SMF and MMF, guide light through their cores using total internal reflection at the core-cladding boundary, enabling linear light transmission [51]. However, in NCF, there is no total internal reflection as there is no boundary between the core and cladding. Instead, light propagates through the entire cross-section of the fiber [9]. This difference in structure results in unique light propagation characteristics.

3.1 No-Core fiber structure

In NCF, each light mode has a different path and speed, which may cause modal dispersion. This characteristic that makes NCF more sensitive to changes in the surrounding environment. Since the light spreads throughout the fiber cross-section and interacts directly with the external environment, NCF becomes responsive to changes in the external refractive index [53]. This high sensitivity, combined with a simpler manufacturing process, i.e., structural modification is not required, makes NCF an attractive for optical sensor applications [9]. NCF offers great potential in the development of more effective and efficient optical sensors for detecting environmental parameters such as temperature measurement [16, 17], pressure [53], strain [24, 54], refractive index [18, 20], and many more.

Figure 3 illustrates the optical fiber sensor using NCF. The simplest NCF-based sensors can be made by splicing a small section of NCF between two conventional optical fiber segments. This configuration typically uses SMF or MMF as the input and output segments, with the NCF placed in the middle as the sensing element. This structure creates a “sandwich” array consisting of SMF-NCF-SMF [55, 56] or MMF-NCF-MMF [22, 57]. In this configuration, light from the input fiber (SMF or MMF) enters the NCF segment. Since the NCF does not have a core-cladding structure, the light spreads throughout the fiber cross-section and interacts directly with the surrounding environment. These interactions cause changes to the output light characteristics, such as phase, intensity, or mode pattern, which depend on the physical or chemical parameters around the NCF. After passing through the NCF segment, this modified light then enters the output fiber (SMF or MMF) for further analysis.

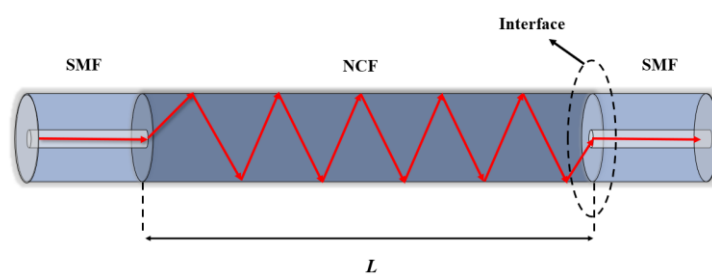


Figure 3 Schematic diagram of SMF-NCF-SMF structures.

The sensitivity and measurement range of the sensor can be optimized by adjusting the length and diameter of the NCF segment [58]. Analysis of changes in the transmission or reflection spectra, such as wavelength shifts or intensity variations, allows quantification of the measured parameters. Simplicity of fabrication, flexibility of application, and high sensitivity make this NCF-based sensor an attractive option for various sensing applications in the environmental, biomedical, and industrial fields.

3.2 Plasmonic effect on no-core fiber

The absence of core in NCF makes the light entering the fiber propagates in various modes and spreads across the fiber's cross-section. For example, when NCF is spliced between SMF, it produces unique light propagation due to multimode interference effect known as self-imaging phenomenon [56, 59]. When light enters the NCF, a number of guided modes are excited simultaneously, and the interaction between these modes produces an interference pattern that spreads along the fiber [60].

Under certain conditions, constructive interference causes the light energy to refocus along the central axis of the NCF, thus forming a replica of the original image, called a self-image. From a theoretical point of view, the position at which the self-image is formed is highly dependent on the length of the NCF. Therefore, this parameter needs to be determined accurately so that the self-image can be

formed at the desired location [61]. If the position of the self-image exactly coincides with the NCF/SMF output interface, then the insertion loss can be minimized and the interference information can be extracted optimally [62]. Conversely, if the self-image is formed before or after the interface, the intensity of light that is successfully reflected back to the SMF will be reduced [63].

In addition to the self-imaging phenomenon, NCF also enhances the role of evanescent waves from the light it transmits [9]. These evanescent waves can interact with external absorbing media, thus causing attenuation of the electromagnetic power. The magnitude of the power transmitted in NCF can be explained using the Lambert–Beer absorption law [64]:

$$P(l) = P_i e^{(-f\alpha l)} \quad (10)$$

where P_i is the input power, f is the fractional power of light within the NCF, α the external medium absorption coefficient, and l is the NCF length.

The evanescent field is a component of the electromagnetic field that decays exponentially from the fiber surface to the surrounding medium. This interacts with materials near the fiber surface [65]. In NCF, the evanescent wave decays exponentially from the outer surface of the fiber with a certain penetration depth:

$$d_p = \frac{\lambda}{2\pi \sqrt{n_{co}^2 \sin^2 \theta_i - n_{cl}^2}} \quad (11)$$

where θ_i is the angle of incidence of the light beam at the core-sheath interface, n_{co} is the refractive index of the fiber core and n_{cl} is the refractive index of the sheath. This penetration depth determines how far the evanescent field enters the outer medium and how strongly it interacts with the surrounding environment.

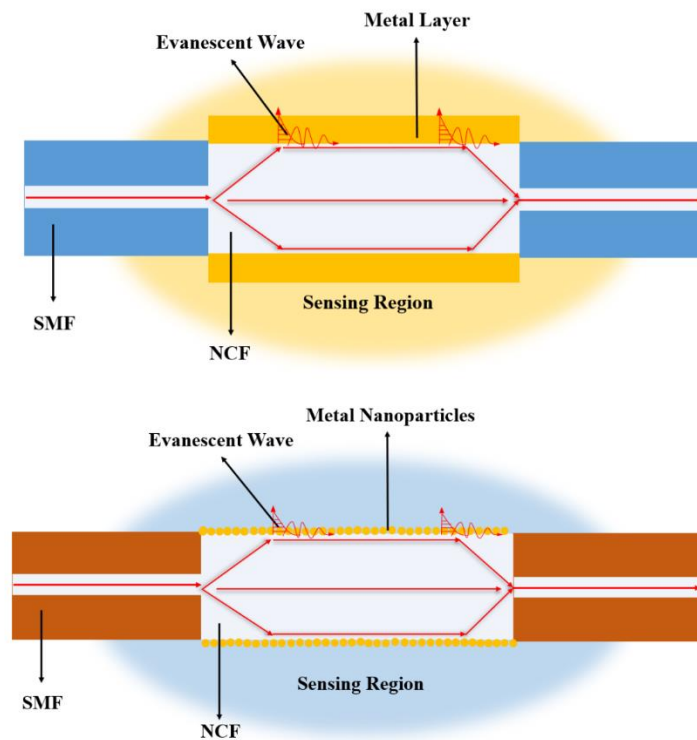


Figure 4 (a) SPR and (b) LSPR effects on NCF.

Plasmonic effects such as SPR and LSPR occur when respectively metal films and metal nanoparticles are coated on the surface of NCF, as shown in Figure 4. In the SPR mechanism, a continuous metal layer, usually in the form of thin films, is coated on the fiber surface. When light propagates inside the NCF, the evanescent field formed on the surface will interact with the metal layer [66]. If the momentum conditions of light and surface plasmon waves satisfy the matching conditions, then the light energy will be transferred to the surface plasmon waves propagating along the interface of the metal and the external medium [67]. Under these resonance conditions, maximum energy absorption occurs. The wavelength at which this maximum absorption occurs is called the SPR resonance wavelength.

Unlike SPR, the LSPR mechanism occurs in metal nanoparticles coated on the surface of NCF. When an evanescent field interacts with these nanoparticles, the free electrons within the nanoparticles undergo collective oscillations. These oscillations occur at specific frequencies called plasmon resonance frequencies. When resonance is reached, maximum absorption or scattering of light occurs at specific wavelengths [68]. Because these resonances are local to each nanoparticle, LSPR is very sensitive to changes that occur very close to the particle surface.

4. Current outlook of plasmonic -activated NCF sensors

When plasmonic materials in the form of thin films or nanoparticles are applied to the surface of these fibers, the interaction between light and plasmonic materials allows unique optical phenomena, such as SPR or LSPR, to occur. The functionalization of plasmonic materials on NCFs aims to increase the sensitivity of the sensor in detecting changes in the surrounding environment.

The functionalization of plasmonic materials in SPR-based NCFs is generally done by coating plasmonic materials in the form of thin films on the surface of optical fibers. This process aims to create an active layer that can respond to changes in the medium around the fiber, resulting in plasmon resonances that are measured as optical signals. The most commonly used plasmonic materials are noble metals, such as Ag film [69-71] or Au film [32, 57, 72]. These materials are selected due to their excellent ability to produce surface plasmon effects at visible wavelengths of light.

A recent research conducted by Yin et al. [73] reported that a compact two-channel SPR-based optical fiber sensor was designed to simultaneously detect refractive index and temperature. The sensor utilized two separate channels: one channel is coated with Ag film for refractive index measurement, while the other channel uses a combination of Ag and polydimethylsiloxane (PDMS) film for temperature measurement. The results suggested that the sharing of Ag film with different refractive index did not affect the accuracy of the sensors. Tests on glucose solution with refractive index of 1.333-1.375 inferred that the SPR at short wavelengths shifted as refractive index changed. A maximum refractive index sensitivity reached 3039 nm/RIU. For temperature measurements in the range of 0-70°C, the SPR at long wavelengths blue-shifted with increasing temperature. A maximum temperature sensitivity of 3.53 nm/°C was obtained. The sensor was capable of measuring refractive index and temperature without inter-channel interference.

A study conducted by Zheng et al. [57] developed a MMF-NCF-MMF structure-based sensor to detect human Immunoglobulin G (IgG) by utilizing the SPR phenomenon. The SPR phenomenon resulted from the interaction of light at the interface between the dielectric layer and Au film, with an optimal NCF length of 12 mm. To enhance the detection sensitivity of IgG, researchers modified the sensor surface using polyelectrolyte self-assembled multilayers (PSAMs) composed of styrenesulfonate sodium salt and diallyldimethyl ammonium chloride (PDDA). When testing with the goat anti-human immunoglobulin G-human immunoglobulin G bio-conjugated pair, the sensor achieved a sensitivity of 57.06 nm/(mg/ml) and a limit of detection (LOD) of 1.75 µg/ml.

The plasmonic phenomenon utilizing NCF structures has become the focus of various studies, as summarized in Table 1. The table shows a comparison of research on the use of plasmonic materials in NCF and their application as sensors, where most of the studies focused on the development of refractive index and temperature sensors. Several SPR-based sensors have been developed to enable simultaneous measurement of two parameters [32, 67, 73-77]. One example of recent research was conducted by Li et al., [67] who designed a dual-channel optical fiber sensor with a cascade structure configuration. In this design, Ag-coated NCFs were used for refractive index sensing, while NCFs modified with Ag, CeF₃, and PDMS were used for temperature detection. In the temperature range of 5-100°C and the refractive index range of 1.33-1.40, the dual-channel sensor showed a maximum sensitivity of 5.4 nm/°C for temperature measurement and 4400 nm/RIU for refractive index measurement.

Compared to SPR which requires a continuous metal layer at in the form of film, LSPR offers the ability to be customized through the control of nanomaterial parameters such as dimensions, morphology, and material type allowing for the setting of resonant wavelengths and optimization of sensor sensitivity for specific applications [35]. With dimensions between 1-100 nm, these nanomaterials offer a new approach in sensor technology [3]. The distinctive physical and chemical properties at the nanoscale are the main differentiators of nanomaterials from bulk materials, and this characterizes their special properties [78]. In the context of LSPR-based NCF sensors, plasmonic nanomaterials serve as the main element that triggers LSPR. This phenomenon occurs when electric field of the light interacts with free electrons on the surface of metallic nanomaterials, creating collective oscillations that are extremely responsive to environmental changes [43]. This sensitivity is utilized to detect changes in refractive index or the presence of target molecules with high precision. The variety of nanomaterials used in LSPR phenomena covers a wide spectrum, each with its own advantages. Among the various types of nanomaterials, precious metal nanoparticles, specifically gold nanoparticles (AuNPs) and silver nanoparticles (AgNPs), are the most commonly used.

Table 1 Current State of Plasmonic-Activated NCF Sensors

Plasmonic Materials	Optical Fiber Structure	Excitation Type	Purpose of Detection	Detection Sensitivity	Ref.
Au film	MMF-NCF-MMF	SPR	Human immunoglobulin G	57.06 nm/(mg/ml)	[57]
Au film	MMF-NCF-MMF	SPR	pH	32.31 nm/pH	[72]
Au + PDMS	MMF-NCF-MMF	SPR	Temperature and glucose	2.904 nm/°C and	[74]
Ag film	MMF-NCF-MMF			2.882 nm/ %	
Ag+Cu composite film	MMF-NCF-MMF	SPR	Refractive index	3957 nm/RIU	[42]
Cr film and Au film	MMF-NCF-MMF	SPR	Refractive index	11792 nm/RIU	[79]
Au film	MMF-NCF-MMF	SPR	Refractive index	1582.5 nm/RIU	[80]
Cr + Ag	SMF-NCF-SMF	SPR	Refractive index	3234 nm/RIU	[81]
Ag + ZnO	MMF-NCF-MMF	SPR	Ultraviolet	-1.462 nm/(mW/cm ²)	[82]
Ag film	MMF-NCF-MMF	SPR	Refractive index	5228.21 nm/RIU	[70]
Ag + PVA + PDMS	NCF	SPR	Humidity and temperature	8.60 nm/%RH and 7.40 nm/°C	[69]
Au	MMF – NCF – MMF	SPR	Refractive index and temperature	3364 nm/RIU and	[32]
Au film + PDMS	(U-Shaped)			3.26 nm/°C	
Ag film	MMF – NCF – MMF	SPR	Refractive index	3039 nm/RIU	[73]
Ag + PDMS	MMF – NCF – MMF			3.53 nm/°C	
ZnO/silver film	MMF – NCF – MMF	SPR	Curvature sensor	0.4424 dB/m ⁻¹	[65]
Sodium + PMDS	MMF – NCF – MMF	SPR	Refractive index and temperature	7977 nm RIU ⁻¹ and 7.86 nm/°C	[83]
Ag – Au + PMDS	MMF – NCF – MMF	SPR	Refractive index and temperature	3231 nm/RIU and 6.68 nm/°C	[84]
Ag film	MMF – NCF – MMF	SPR	Refractive index and temperature	2121.43 nm/RIU and -0.32 nm/°C	[85]
Au/MIP	SMF-NCF-SMF	SPR	Isopropanol Vapor	0,014 nm/ppm	[86]
Ag film	MMF-NCF-PCF-MMF	SPR	Refractive Index	5255.2 nm/RIU	[87]
Ag/WO ₃ /PDMS			Temperature	4.5 nm/°C	
Sodium/PMMA	D-shaped NCF	SPR	Refractive Index	10400 nm/RIU	[77]
Sodium/PDMS			Temperature	15.5 nm/°C	
MoS ₂ /PMDS/Ag film	MMF – NCF – MMF	SPR	Temperature	-2.6 nm/°C	[75]
Ag film			Glucose	2.4 nm/%	

Table 1 (continued) Current State of Plasmonic-Activated NCF Sensors

Plasmonic Materials	Optical Fiber Structure	Excitation Type	Purpose of Detection	Detection Sensitivity	Ref.
Ag film	MMF – NCF – MMF	SPR	Refractive Index	4400 nm/RIU	[67]
Ag/CeF ₃ /PMDS			Temperature	5.4 nm/°C	
Ag + ZnO film	MMF – NCF – MMF	SPR	Curvature	0.1632 dB/m ⁻¹	[76]
			Refractive Index	7600 nm/RIU	
AuNSs	SMF–tapered NCF–SMF	LSPR	Refractive index	254.42 nm/RIU	[68]
AuNPs	MMF–NCF–MMF	LSPR	Refractive index	523.14 nm/RIU	[31]
Au–SiO ₂	MMF–NCF–MMF	LSPR SPR	pH	13.4 T%/pH	[88]
ZnO nanostructure	MMF–NCF–MMF	LSPR	Refractive index	799.42%/RIU	[89]
G-NPs	SMF–NCF–SMF	LSPR	Temperature	-0.104 nm/°C	[71]

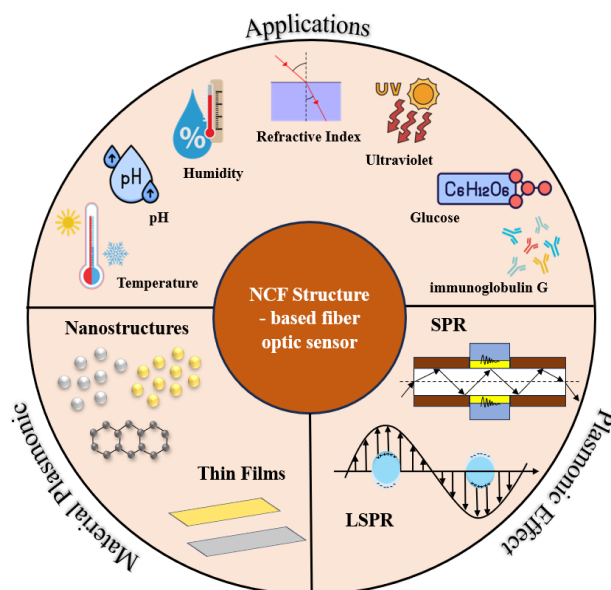
In recent years, there has been very little research utilizing LSPR-based NCF sensors (see Table 1). Wang et al. [31] developed an optical fiber sensor based on the LSPR phenomenon. The sensor was made by splicing small fraction of NCF to MMFs, which then used a self-assembly method to immobilize AuNPs in the NCF region. With simple methods such as splicing and chemical surface modification, this sensor offered an economical and practical solution for LSPR-based optical sensor applications. During the assembly process, a series of absorbance spectra were recorded, showing a wavelength shift towards longer wavelengths and an increase in the absorbance peak. The sensor had distinct sensitivities in two refractive index ranges, i.e., 121.88 nm/RIU for refractive index range of 1.33-1.37 and 523.14 nm/RIU for refractive index range of 1.37-1.42 RIU. The sensor also had low detection limits of 1.64×10^{-3} RIU and 3.82×10^{-4} RIU, which demonstrated its ability to detect small changes in refractive index with high accuracy.

On the other hand, there was another research conducted by Chauhan and Singh [89] where they explored the use of ZnO nanorod-shaped plasmonic materials to improve the performance of NCF-based optical sensors for refractive index sensing. Through hydrothermal parameter optimization, various morphologies of ZnO nanoparticles were successfully synthesized. This sensor measured the change in intensity of light transmitted through the fiber due to variation in the refractive index of the surrounding medium. The best results were obtained from vertically oriented ZnO nanorods, showing high sensitivity that reached 799.42%/RIU with detection range of 1.33-1.40.

Then recently, Hidayat et al. [68] reported the development of a refractive index sensor based on NCF, which was then tapered and coated with gold nanospheres (AuNSs) to enhance sensitivity. The tapering process was optimized by varying the CO₂ laser power to control the tapering diameter, while AuNS with an average size of 11.26 nm synthesized via citrate reduction method were attached to the tapered NCF surface using thiol functionalization. The results showed that the sensitivity of the unmodified NCF of 50.97 ± 4.68 nm/RIU increased to 254.42 ± 20.75 nm/RIU after AuNS coating, or approximately fourfold (~400%).

Until now, there has been very little research utilizing NCF-based sensor structures that exploit the LSPR phenomenon, in contrast to SPR which has been widely carried out for various applications. This is mainly due to the unique technical challenges in LSPR sensor development, particularly in terms of synthesis and control of metallic nanoparticles. A key challenge in developments that utilize the LSPR phenomenon is the need for highly precise control of the characteristics of metallic nanoparticles. The LSPR phenomenon is sensitive to the size, shape and composition of the nanoparticles, where small changes in these parameters can influence the performance of the sensor [43]. The nanoparticle synthesis process is a critical stage that requires controlled conditions to produce uniform nanoparticles.

In the synthesis process, parameters such as reaction temperature concentration, precursors, and synthesis time must be carefully controlled. Aggregation of nanoparticles should also be avoided as it can reduce the sensitivity of the sensor. In addition, the nanoparticle deposition process on the NCF surface should produce a uniform layer to optimize the sensor performance. Despite facing various challenges, the development of NCF-LSPR sensors remains promising due to its potential in miniaturization and high sensitivity. Advances in nanoparticle synthesis techniques and characterization methods are expected to overcome these technical challenges, enabling the development of more effective NCF-LSPR sensors for various applications.

**Figure 5** Key features in plasmonic-based NCF sensor.

Based on the description above, Figure 5 illustrates a comprehensive picture of the current status of the development of fiber sensor technology based on no core fiber that utilizes plasmonic optical effects. The plasmonic effects applied include SPR and LSPR, with the plasmonic materials used in the form of nanostructures such as AuNPs, AgNPs, G-NPs, and ZnO NPs, as well as thin films such as Au Film and Ag Film. This technology has been applied in various applications, including the measurement of refractive index, temperature, humidity, pH, ultraviolet light, glucose, and detection of Human Immunoglobulin G.

5. Conclusion and future potential

Recent developments related to NCF structure-based sensors utilizing the plasmonic effect have been reviewed in this paper. The discussion covers the basic principles of plasmonic effect (SPR and LSPR), NCF sensing mechanism, as well as the current status of plasmonic-based NCF sensors. Research progress shows that sensors with NCF structures that utilize the plasmonic effect have been widely used in the measurement of various applications. In this sense, the majority of publications focused on refractive index sensors (Table 1). Most studies still utilized the SPR phenomenon rather than LSPR, this might be due to the technical challenges in LSPR sensor development especially in terms of controlling the metallic nanoparticles' size and shape to achieve the best plasmonic properties. Nonetheless, LSPR-based NCF sensors have great potential to be developed as they provide flexibility in design through optimization of nanostructure parameters such as size, shape, and material composition. This capability allows customization of the resonant wavelength and enhancement of sensitivity as per the application needs.

The future development prospects of plasmonic effect-based sensors are promising, especially with advances in nanostructure fabrication techniques and surface functionalization methods. Some potential development directions include sensor design optimization to improve sensitivity and selectivity, as well as the development of more controlled and reproducible fabrication methods to ensure nanostructure quality. In addition, the development of new NCF structures and materials for plasmonic effects would be a promising strategy to expand the utilization of such sensors in various fields, such as chemistry and biosensors. Integration with other technologies may also lead to the development of multianalyte sensors, while miniaturization and the development of portable systems will enable the application of sensors in the field. As the technology and characterization methods continue to evolve, it is expected that the technical challenges in the development of plasmonic effect-based NCF sensors can be overcome, opening up opportunities for wider applications in the future.

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7. References

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