

Recent Progress in Plasmonic Assisted Fiber Bragg Grating Sensor for Food Security Applications

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Food security and related environmental safety issues have become a central concern all over the world with the globalised trade of food commodities. Consumer awareness arises regarding the foodborne pathogens and other toxic substances, such as Aflatoxins, mycotoxins, pesticides and veterinary drug residue, that will lead to more hazardous health effects. This article reviews the potential of plasmonic-based Fiber Bragg grating (FBG) for food security applications by focusing on grating designs and fibre optics structures, material properties, sensitivities and their recent applications. In food security, the current usages of plasmonic FBG-based sensors have covered diverse applications such as thrombin detection, protein detection, smart farming (humidity and temperature detection), glucose detection, contamination of heavy metal ions in drinking water detection, salinity monitoring and methane sensing. Among various designs of gratings, tilted FBG (TFBG) shows an outstanding sensing property owing to the combination of spectral resonances and SPR, in which resulted in the excitation of strong evanescent waves. This study suggests the hybrid structure of multimode fibre (MMF)-TFBG produced in better sensitivity than single-mode fibre (SMF)-TFBG owing to its large numerical aperture that increases the mode field diameter and the number of propagating modes. In conclusion, the plasmonic FBG-based sensor is a promising candidate for food security monitoring with regard to its outstanding properties, including simple structure, portability and high-sensitivity.

Keywords: Surface plasmon resonance; Fiber Bragg grating; optical fibre; sensor; food security

I. INTRODUCTION

Food is one of the important elements for the survival of human beings. Statistics by the Department of Statistics Malaysia shows the growing population of Malaysian in 2019 at 32.5 million compared to 31.6 million in 2016 (<https://www.dosm.gov.my>). These numbers indicate that the increment of food supply demands in line with the population due to the factor that food is essential part for our physical wellbeing. The increasing for food production and manufacturing, safety and security are an issue that need to be considered. The ingredients, concentrations and hygiene's control should be strictly taken to avoid foodborne cases, diseases such as diabetes, Alzheimer's and other by detecting the biomolecules, aptamers and bacteria, pesticide confined

in the food (Moon *et al.*, 2018). Thus, a real-time, small, highly sensitive food sensor is needed to overcome and tackle this issue.

There are many high-end analytical technologies have been introduced for food safety monitoring, including chromatography methods such as gas chromatography (GC), high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometer (GC-MS) and liquid chromatography-mass spectrometer (LC-MS). Spectrophotography, electrochemical, immunological detection like enzyme-linked immunosorbent assay (ELISA) as well as lateral immunoassay flow for detection of Aflatoxins (AFs) toxic group (Moon *et al.*, 2018; Zeng *et al.*, 2018; Zhang *et al.*, 2018) are other popular alternatives that have been employed for food safety monitoring and

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measurement. However, they are time-consuming, expensive, laborious and well-trained personnel is required. Developing areas and countries lacking in specialists and facilities, makes it quite incompatible for them to employ these methods (Zeng *et al.*, 2018).

Surface plasmon resonance can be defined as an oscillation of charged density that occurs at the interface of two mediums, i.e., metal and dielectric. The unique characteristics of plasmonic-based optical fibre sensors being fast responses, high sensitivity, immunity to electromagnetic interference, real-time detection and wide sensing parameters such as chemicals, temperature, strain, pressure and biological species have come an interest in researchers to utilise it for food safety and security sensor (Mukhtar *et al.*, 2017a; Rivero *et al.*, 2017; Zeng *et al.*, 2018). In addition, optical fibre deployments eventually replaced the traditional substrate, such as prism for SPR sensor (Adanyi *et al.*, 2017; Mukhtar *et al.*, 2017b).

Fiber Bragg gratings (FBGs) are formed by a periodic modulation of the index of refraction of the fibre core along the longitudinal direction and work as a sensor based on the principle of wavelength shift (Sahota *et al.*, 2020). It can reflect specific light wavelengths known as Bragg's wavelength at resonant frequency, which satisfied the Bragg's resonance condition and transmitted the others. Owing to their numerous advantages, such as immune to electromagnetic interference, anti-corrosion and capable to detect distributed measurement, FBGs are widely used as sensors for various applications (Rosman *et al.*, 2020; Zhao *et al.*, 2019). Recently, FBG combined with various nanomaterials and modified structures are commonly used in sensing applications, including food security, structural health monitoring, water safety and cancer detection (Burgmeier *et al.*, 2015; Grwambi, 2020; Mukhtar & Zailani, 2020).

In building a surface plasmon resonance (SPR) based FBG sensing platform, the wavelengths of the light source, optical fibre grating configurations, material of coating and the coating layer thickness plays a critical contribution. In facts, the advancement of compact, flexible and highly integrated optical fibre sensor has attracted many attentions. The main objective of this study is to review and to analyse recent works on the material properties, grating design, fibre optics

structures and application of plasmonic-assisted FBG in food security area. We believe this review will benefit on the future research of sensing technologies to broaden the potential development of high-sensitivity plasmonic FBG-based sensors.

II. FOOD SECURITY

Food security is crucial to ensure the food we consume and eat is safe. For the food to be considered as safe, there should be an assurance that it will not cause harm to the consumer. Individuals or groups of people taking part in production, processing, trade and food consumption in the whole food chain have the responsibility to provide safe, traceability, nutritional and healthy food, from the primary production to the final consumption. The responsibility must extend to the end-consumer, who should be educated to ensure food is stored properly, prepared hygienically and respects the food shelf lives (Grwambi, 2020). The main areas interconnected with food security are soil and plant sensing, management of farm and post-harvest applications (Kayad *et al.*, 2020). Foodborne illness caused by microbiological, chemical and physical pathogens, such as exotoxin and enterotoxins from *Escherichia Coli* and *Salmonella*, pesticides and also highly hazardous toxins like aflatoxins, ochratoxins and patulin, indirectly may lead to a major economic burden due to medical, hospitalisation and inspection costs (Fuerter *et al.*, 2016; Elgueta *et al.*, 2020; Grwambi, 2020; Paniel *et al.*, 2019; Srinivasan *et al.*, 2017). These facts proved that food industry currently in need of novel diagnostic and biosensing nanotechnology sensor, which can be actively integrated in various food chain stages as well as on-site application to deliver nutritional food product from farm to fork.

III. WORKING PRINCIPLE OF SURFACE PLASMON RESONANCE SENSOR

In 1957, Ritchie introduced a term known as surface plasmon (SPs). The sensing principle of surface plasmon can be divided into propagating surface plasmon resonance (SPR) and localised surface plasmon resonance (LSPR) (Guo 2017).

A. Propagating Surface Plasmon Resonance

Surface plasmon resonance (SPR) is an underlying principle that is widely used in sensing application. There are two types of prism configuration, which are Otto and Kretschmann configuration (Gupta & Kant, 2018). Kretschmann is the most common approach to excite the surface plasmon wave on thin metal films due to its simplicity (Mukhtar *et al.*, 2017b). Electromagnetic waves stimulate the resonant oscillation of the conduction electrons at the interface between dielectric and metal. Under resonance condition, the surface plasmon polaritons are excited by the present of evanescent wave. When the incident light's constant propagation is equal to the collective oscillation of metal surface electrons, their momenta is phase-matched and thus resonance occurs. This occurrence will lead to a highly sensitive SPR to variations in refractive index (RI) (Guo *et al.*, 2017).

B. Localised Surface Plasmon Resonance

Localised surface plasmon resonance (LSPR) occurs when the cloud of free electron's collective oscillation is confined in the metal nanoparticles or nanostructures layer. Interaction of free electrons and incident light's electric field in the metal nanoparticles triggered the free electrons' displacement causing them to separate (Guo *et al.*, 2017; Samsuri *et al.*, 2017). A slight variation of surrounding medium refractive index may affect the wavelength position of LSPR attenuation band and intensity. These changes in refractive index are observed by the analytes or biomolecules' adhesion to the nanoparticles surface leading to shift in LSPR peak absorbance wavelength that can be described as stated in equation (1):

$$\Delta\lambda = m (\Delta n) [1 - \exp(-2d/l_d)] \quad (1)$$

where $\Delta\lambda$ is the peak absorbance wavelength shift correspond to refractive index changes (Δn), is the sensitivity of refractive index, d as the thickness of absorbed layer and l_d represents length of decay of associated electromagnetic field. LSPR is typically associated with well-dispersed nanoparticles and presents a strong EM-field around the particles surface, meanwhile SPR shows an EM-field capable of reaching

hundreds of nanometers. Note that these two types of plasmonic resonances present very different optical properties, as the sensitivity to refractive index changes in the surrounding medium (Dos Santos *et al.*, 2023). These phenomena have been utilised in various chemical sensing and biosensing applications, including clinical diagnostics, food safety and environmental monitoring (Wei *et al.*, 2017).

IV. TYPES OF FIBER BRAGG GRATING

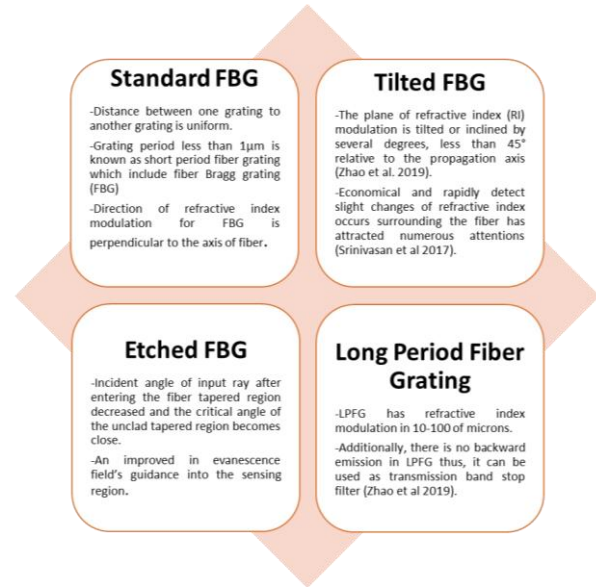


Figure 1. Various types of FBGS and their properties

As light propagates through the fibre, the fibre grating-assisted SPR sensor preserves the structural integrity and also retains the circular symmetry in order to remove the polarisation dependence of the fibre. These facts instigated the employment of fibre grating in SPR sensing configuration (Gandhi *et al.*, 2019). Figure 1 lists the properties and differences between various structures of FBG, such as standard FBG, tilted FBG, etched FBG and long-period fibre grating. The effective refractive index and period grating length of the FBG influenced the change in the surrounding refractive index that led to the changes in the grating resonance condition. The combination of SPR and LPFG has been verified can improve the sensitivity of the sensor owing to its longer grating period, which can couple more energy into the co-propagating cladding mode and, hence, further improve the excitation efficiency of the SPR (Zhao *et al.*, 2019).

V. PLASMONIC NANOSTRUCTURED MATERIALS IN OPTICAL SENSING

Metal nanoparticles, nanotubes, fullerenes, nanofibres, nanomembranes, nanorods and nanoflowers are included in nanomaterials and have a high-volume ratio's surface, which efficiently enable interaction of analytes molecules with entities in the sensing surface compared to bulk layers (Fuertes *et al.*, 2016). Strong plasmonic response collaborated with small and unique properties of nanomaterial, enabling it to be applied for sensor sensitivity improvement (Zhao *et al.*, 2019). The surface of nanostructures can be functionalised by tuning the properties of nanoscale materials, such as size, shape, and composition to create specific locks with the biomolecules or analytes necessary in distinguish dangerous pathogens (Kagan, 2016). For example, gold (Au) nanomaterials such as gold nanoparticles (AuNPs), gold nanowires (AuNWs), Au nanosphere, gold nanorods (AuNR) and gold nanoislands (AuNI) are the best plasmonic material to use in the SPR sensor for Covid-19 detection. These nanomaterials' structures are suitable to be used in SPR sensors since they provide high sensitivity, low level of detection (LOD), fast time response, and high selectivity and can be doped with other materials such as graphene, GO, and other types of nanoparticles (Fendi *et al.*, 2023).

Coelho *et al.* (2016) investigated the potential performance between two types of fibre optics namely LPFG-coated titanium dioxide (TiO₂) and SPR-based SMF sensor, for thrombin-based aptamer binding sensing. The SPR-based SMF sensor was fabricated by coating the fibre optics with 15 nm thickness of gold thin film followed with 100 nm thickness of titanium dioxide (TiO₂). The significant output of this study indicates that the SPR-based sensor exhibited excellent sensitivity up to 3143 nm/RIU compared to TiO₂-based LPFG with the value of sensitivity only about 204 nm/RIU.

Integration of nanotechnology and nanosensors for food security can be implemented as a processing sensor and intelligent packaging (IP) to control their quality during various stages of logistic process until to the final consumer (Fuertes *et al.*, 2016). Burgmeier *et al.* (2015) successfully immobilised gold nanoshells on the etched FBG for refractive index measurements. The output of this study resulted in a

slightly increased Bragg wavelength shifting about 1.5% from 13.3 nm/RIU to 13.5 nm/RIU utilising the LSPR effect generated by the gold nanoshells coated fibre optic sensor with different surface refractive index (SRI). One of the techniques that had been used to enhance the sensing ability of the fibre optic sensor is by applying macro bending on the plasmonic coated fibre. This macro bending effect creates the frustrated total internal refraction that leads to the excitation of evanescent waves (Kamarulzaman & Mukhtar, 2020; Mukhtar *et al.*, 2017c). For example, the deployment of triple loop rings fibre optics coated with AuNPs and GO exhibits a maximum sensitivity of up to 69.17% due to the formation of a large evanescent field around the loop area and intense SPP excitation (Mukhtar *et al.*, 2021). The intensity of the evanescent waves at the surface of the optical fibre is enhanced with the presence of graphene, thus increasing the interaction of the SPR wave and pathogens or bacteria confined in the food. Wei *et al.* 2017 investigated the role of graphene layer that had been hybridised with silver to the optical sensing properties. The electric field penetration depth into the sensing medium of Ag/graphene structure increased about 4.03% from 1210 nm to 1260 nm in comparison with the absence of graphene layer. This result indicated the advantages of graphene in enhancing sensing properties due to its outstanding benefits such as chemical flexibility, high sensing features, high conductivity, transparent nature, and high surface area makes it suitable to immobilise desired bioreceptors and adjust sensor's sensitivity (Yildiz *et al.*, 2021).

Eng *et al.* (2016) proposed a high-resolution of tilted Fiber Bragg grating surface plasmon resonance sensor using single-sided 50nm gold coatings, which achieved limit of detection 3×10^{-6} RIU and yield a high sensitivity up to 3.34×10^4 dB/RIU. Mukhtar *et al.* (2018a) reported a hybrid of gold-graphene oxide-gold nanoparticles (Au/GO/AuNPs) films plasmon absorbance for greater SPR excitations. Au/GO is a great candidate for optimising the plasmon absorbance due to GO hydrophilic properties, while the Au/AuNPs bilayer is not suitable for this purpose as its attachment difficulty between the two layers. Apparently, the introduction of hybrid material consists of metal nanoparticles and other materials, such as graphene and TiO₂ able to enhance the sensing properties of the proposed sensors.

VI. SURFACE PLASMON RESONANCE (SPR) BASED FBG SENSOR FOR FOOD SECURITY

A. FBG-Based Sensor for Food Security Applications

Apart from access to nutritious food, other important issues that have been discussed in food security are the quality of food, including contamination level and packaging safety. Smart farming that consists of combination technologies in one system has been proven able to boost the production of farm crops and livestock while maximising profit and minimising the cost of production. In the food security field, smart technologies are very helpful in monitoring the growth of plants. Lo Presti and co-workers introduced the innovation of wearable sensors for monitoring elongation, microclimate, and plant stress. By integrating three different types of FBG that consisted of dumbbell shape, chitosan-coated fibre optics and bare FBG, the developed sensor system was able to detect important factors of plant growth. This smart farming technology displayed outstanding performance with high sensitivity as shown in Table 1 (Lo Presti *et al.*, 2021).

Chitosan has been recently used in optical sensing applications due to its large swelling capacity in water and structural ability to regulate moisture absorption (D'Amato *et al.*, 2021). Humidity sensors utilising chitosan-coated FBG developed by D'Amato and co-workers indicated that the viscosity of chitosan is an important parameter in developing high-sensitivity sensors. Deposition of chitosan on FBG adopting qualitative filter paper has proved able to improve the adhesion of the chitosan on the fibre and enhanced the permeability of the substrate with sensitivity up to $(64.7 \pm 5) \%$ /RH.

Owing to its grating structure that resulted in outstanding characteristics to detect small changes in refractive index, FBG is one of the popular devices that was deployed in food security for humidity and temperature detection. The introduction of material coated on FBG exhibited an increase of the sensor's sensitivity. ORMOCER® (OR)-coated Fiber Bragg grating (FBG) sensor encapsulated with stainless steel had been proposed for relative humidity (RH) sensing by Guo *et al.* (2021). The introduction of an inorganic-organic hybrid polymer coated on the FBG enhanced the capability of common FBG due to the ability of ORMOCER® in absorbing water molecules from the air (Guo *et al.*, 2021).

Overall, the usage on FBG as safety monitoring tools in food security field is growing until today. It covers various wide areas, including smart farming to monitor plant growth and detection of the temperature and humidity level of the samples. For the sensitivity optimisation of the sensors, significant materials like chitosan and inorganic-organic hybrid polymer coated on FBG exhibit outstanding sensing performance. Besides, changing the structure of FBG to the dumbbell shape and introducing hybrid types of FBG in one system shows the sensitivity enhancement of the proposed sensor for food security applications.

B. Surface Plasmon Resonance (SPR) Based FBG Sensor for Food Security Applications

Diagnostic of SPR-based sensors cooperated with the numerous advantages of optical fibre-based sensors, which offer label-free, rapid detection, miniaturised, robust, flexible, nanoscale and inexpensive have profound applications in ensuring the quality, safety and security of food products (Caucheteur *et al.*, 2016; Kagan *et al.*, 2016). The plasmonic-based fibre grating sensors are operated in infrared instead of the visible light spectrum and have higher spectral sensitivities, which results in overall performance improvement compared to the fibre optic without the presence of a grating structure. These comparatively higher spectral sensitivity and narrow spectral comb improved the resolution up to 10^{-8} RIU leading to an increase in the figure of merit (FOM), which made them more competent for multiplexing purposes (Lobry *et al.*, 2020; Rivero *et al.*, 2017). These optical fibre sensors can measure high resolution mostly due to the use of single-wavelength and narrow linewidth interrogation technique. In fact, it can be achieved as the TFBG produced low wavelength attenuation and very dense frequency narrowband frequency comb which can probe various type of perturbations to the fibre and the surroundings as reported by Caucheteur *et al.* (2016).

One of the preferable approaches to generate stronger evanescent waves from the FBG is by modifying the structure of the fibre itself, such as by combining different structures of fibre optics and by polishing or etching the cladding area to expose the core part. For example, the introduction of nanomaterials such as Au, graphene and silver coated on hybrid multimode fibre (MMF)-TFBG achieved greater

excitation of surface plasmon than single-mode fibre (SMF-TFBG) with 18.30% improvement of sensitivity (Lobry *et al.*, 2020). In sense, the main advantages of MMF compared to SMF are due to its large numerical aperture that increases the mode field diameter and the number of propagating modes (Qi *et al.*, 2022). A side-polished SPR optical fibre sensor for rapidly detecting avian influenza virus subtype H6 (Influenza AIV-H6) in poultry was successfully developed by Zhao *et al.* (2016) and is used as a front-line device in food safety. About 40 nm of gold thin film was coated on the exposed core surface to efficiently monitor the effective refractive index changes of the captured Influenza AIV-H6. Leal-Junior *et al.* (2023) developed an SPR sensor in a D-shaped optical fibre in conjunction with a Fiber Bragg grating (FBG) for salinity monitoring. The sensor was coated with 50 nm gold thin film to generate SPR to detect the salinities of samples through refractive index variation. It was found that these FBG-assisted SPR sensors resulted in an improvement of the salinity monitoring of different samples with sensitivity up to 12.5 pm/°C.

In line with today's modernisation, environmental concerns on the quality of air and water are major issues that should be taken seriously. Heavy metal contamination in drinking water, such as copper ions and lead ions is one of the recent challenges in food security. Samavati *et al.* (2022) proposed a plasmonic-based FBG sensor by deploying gold-coated FBG decorated with Schiff base ligands (SBL) for monitoring the copper ions (Cu^{2+}) concentration in an aqueous solution. This sensor exhibited excellent selectivity and a dynamic range within the acceptable limit for safe drinking water. Zhu *et al.* (2023) introduced the thrombin aptamer functionalised gold-coated tilted Fiber Bragg gratings (SPR-TFBGs) to detect the presence of lead ions in drinking water by varying the concentration of aqueous solution from 0.001 ppb to 10 ppb. This SPR-based TFBG sensor portrayed excellent sensitivity due to its capability to detect the lowest concentration of lead ions at 0.001 pb. The output of these studies validated the significant identities of the plasmonic FBG-based sensors, which are very sensitive yet simple structures that have a bright potential to be commercialised in monitoring contaminated drinking water for domestic use.

Table 1 summarises various types and structures of Fiber Bragg grating based SPR sensors that had been used in food

security. In recent years, the plasmonic FBG-based sensors have been utilised in food security areas, such as for detection of protein, thrombin, heavy metal ions in drinking water and smart farming (humidity and temperature sensing). Statistical analysis of the types of grating structures for monitoring food safety levels is depicted in Figure 2. Clearly, the TFBG is the most favourable structure with 36% of applications owing to its outstanding optical properties in generating a strong evanescent field. Note that only 4% of TFBG without the plasmonic effect had been used in food safety monitoring which indirectly proved the significant sensitivity optimisation as the metal-coated TFBG is deployed. The plasmonic TFBG has a great advantage.

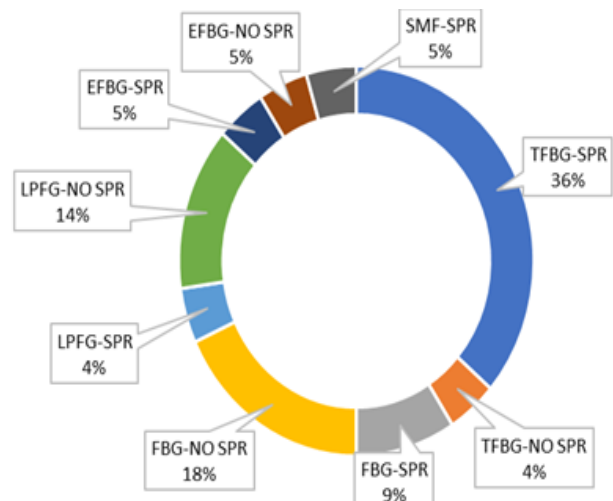


Figure 2. Analysis on the percentage usage of various structures of FBG in food safety

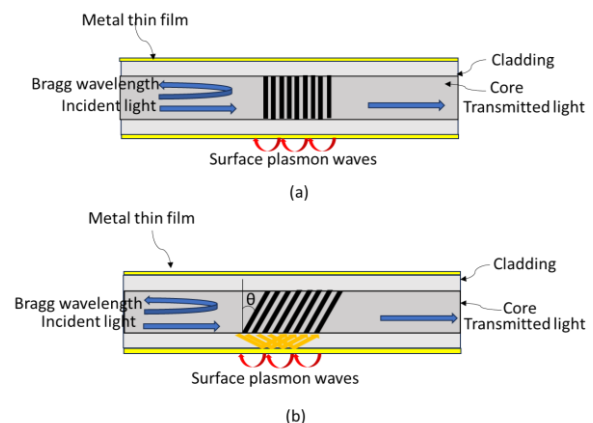


Figure 3. Structure of plasmonic-based FBG (a) basic FBG (b) tilted FBG.

Table 1. Analysis on structures, materials, sensitivity and optical properties of Fiber Bragg grating with various applications in food security

Grating description	Fiber structure	Thickness/Diameter of coating materials (nm)	Sensitivity (dB or nm/RIU)	Wavelength (nm)	Index range	Application /Detection	Ref.
TFBG	TFBG-SPR	Ag thin film, t=50 nm	5.5 dB/(mg/mL)	1440-1560	1.34-1.34	urinary protein detection	Guo <i>et al.</i> , 2016
	TFBG-SPR	Au thin film, t=50 nm	204 nm/RIU	1270-1410	0.92-1.18	ultrasensitive RI sensing in air	Kagan, 2016
	TFBG-SPR	Au thin film, t=50 nm	576.08 nm/RIU	1510-1610	1.32-1.36	glycoprotein measurement	Zhang <i>et al.</i> , 2017
	TFBG-SPR	Ag thin film, t= 30 nm	0.5dB/mM	1450-1550	1.32-1.34	glucose detection	Zhang <i>et al.</i> , 2018
	TFBG-SPR	Au thin film, t=35 nm	688 nm/RIU	1545-1550	1.33-PDA	non-enzymatic D-glucose detection	Lobry <i>et al.</i> , 2019
	TFBG SPR-SMF	Au thin film, t=35 nm	102.03 nm/RIU	1520-1545	1.45-1.46	HER2 protein detection	Lobry <i>et al.</i> , 2020
	TFBG SPR-MMF	Au thin film, t=35 nm	124.89 nm/RIU	1530-1550	1.45-1.46	HER2 protein detection	Lobry <i>et al.</i> , 2020
	TFBG-SPR	Au thin film	-	1525–1610	0.001 ppb to 10 ppb (concentration)	Lead ion in drinking water	Zhu <i>et al.</i> , 2023
FBG	TFBG-MMF	Bare	56.3 nm/RIU	1530-1550	1.45-1.46	HER2 protein detection	Lobry <i>et al.</i> , 2020
	FBG-SPR	Au thin films decorated with Schiff base ligands (SBL)	23.1 ppm/ μ M	1550-1551	-	Cu ²⁺ ions in water	Samavati <i>et al.</i> , 2022
	FBG-LSPR	Au nanoparticles, d=50 nm	-	1310-1550	1.45-1.47	Honey quality detection	Mokhtar <i>et al.</i> , 2021
	D shape POF-FBG	Au thin film, t=50 nm	12.5 pm/ $^{\circ}$ C	1550	1.34-1.345	Salinity monitoring	Leal-Junior <i>et al.</i> , 2023
	Hybrid structure FBG (dumbbell shaped-CH coated-the bare FBG)	Chitosan (CH)	0.04 nm/m ϵ , 0.04 nm/%RH, and 0.01 nm/ $^{\circ}$ C respectively	1533 and 1541	-	Plant growth monitoring (strain, humidity and temperature sensing)	Lo Presti <i>et al.</i> , 2021

	FBG	ORMOCER® (inorganic–organic hybrid polymer)	2.4 pm/%R H and 12.9 pm/°C	1550	-	Humidity and temperature sensing	Guo <i>et al.</i> , 2021
	FBG	Chitosan (CH)	(64.7 ± 5) %/RH	1540 - 1545	-	Humidity sensing	D'Amato <i>et al.</i> , 2021
LPFG	LPFG SPR	Ag thin film, t=50 nm	20dB/RIU	1530-1550	1.42	methane sensing	Wei <i>et al.</i> , 2017
	LPFG	bare	18 dB/RIU	1530-1550	1.42	methane sensing	Wei <i>et al.</i> , 2017
	LPFG	Graphene monolayer	25dB/RIU	1530-1550	1.42	methane sensing	Wei <i>et al.</i> , 2017
	LPFG	TiO ₂ thin film, t=30 nm	204 nm/RIU	1500-1600	1.335 to 1.355	Thrombin detection	Coelho <i>et al.</i> , 2016
EFBG	EFBG	bare	17.4 nm/RIU	1460-1600	-	Thrombin detection	Bekmurzaye va <i>et al.</i> , 2018
	EFBG- SPR	Au thin film, t=50 nm	23.1 pm/μ M	1520–1560	-	Copper ion in water resources	Sawavati <i>et al.</i> , 2022
No grating (SMF)	SMF-SPR	Au thin film, t=16 nm; TiO ₂ , t=100nm	3143 nm/RIU	1500-1600	1.335 to 1.355	Thrombin detection	Coelho <i>et al.</i> , 2016

compared to the bare TFBG, where the generation of stronger electromagnetic energy occurs on the metallic surface. Consequently, this situation will cause the plasmonic TFBG to be more sensitive to the surrounding refractive index (Chen *et al.*, 2021). Figure 3 shows the structure's difference between FBG and TFBG. The grating planes that are blazed at an angle with respect to the fibre-propagating axis allowed light transmitted in the fibre couples with the core mode as well as backward-propagating cladding modes, leading to a series of dense spectral resonances. The combination of spectral resonances and SPR obviously results in the excitation of strong evanescent waves that leads to the high sensitivity performance of the plasmonic-based TFBG sensors in detecting viruses or low concentrations of contaminants in food as indicated in Figure 3(b).

As mentioned in the previous part, SPR only can be generated as light interact with noble metal thin film or nanoparticles. By focusing on the food security field, gold is significantly the most used noble metal with 50% of applications to generate SPR for the sensing purpose (Figure 4). Despite the costly factor, the outstanding properties of gold, such as non-oxidised materials, strong and chemical resistance making it as preferable alternative compared to

silver. Note that, there are few recent research that were carried out without utilising SPR by using other materials like chitosan, graphene, graphene oxide (GO) and titanium dioxide (TiO₂). For example, today, chitosan has become a popular material in sensing applications because of its high stability, biodegradability, non-toxicity, and biocompatibility. We believe the hybridisation of chitosan and noble metal will offer improved barrier, chemical,

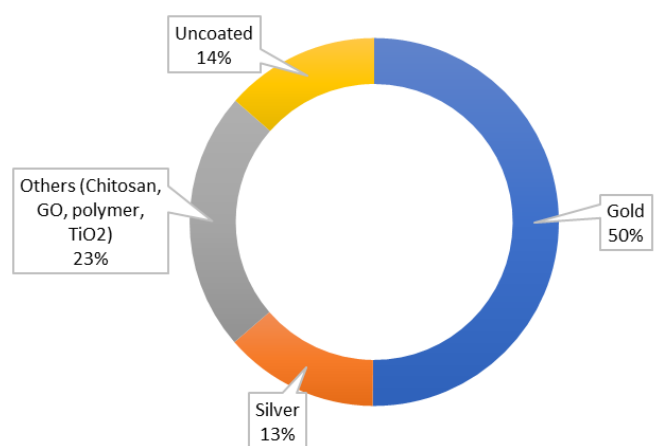


Figure 4. Analysis on the usage of various types of materials in plasmonic-based FBG sensors to generate SPR

thermal, and mechanical properties of the sensors specifically for the food safety monitoring (Mamuk *et al.*, 2023).

In SPR, the characteristics of noble metal plays main important roles to ensure the excitation of plasmon polaritons. Few critical parameters that affected their characteristics including film thicknesses, diameter of metal nanoparticles, synthesis methods, thin film deposition techniques, light operating wavelength and refractive index of waveguides such as prism and fibre optics (Khilmy *et al.*, 2022; Mukhtar *et al.*, 2018b; Murat *et al.*, 2016; Samsuri *et al.*, 2017). The output of this review suggests that highly efficient plasmonic sensor can be developed by employing 35 nm thickness of gold thin film coated on TFBG with maximum sensitivity is $S = 688 \text{ nm/RIU}$ as reported by Lobry *et al.* (2019). Interestingly, the sensitivity of this sensor shows an enhancement up to 70.35% compared to the TFBG coated with 50 nm thickness of gold film (Kagan, 2016). It is noteworthy to highlight that the thin film thickness cannot be too thick or too thin. If the film is too thick (more than 50 nm) it will allow light absorption by the metal itself, which will weaken the excitation of surface plasmon polaritons. Instead of, too thin of film thickness, which is around 30 nm and below will lead to the electron damping issues due to the possibility of thin film's ununiformed thickness during material's deposition procedure (Novotny & Hecht, 2012).

VII. CONCLUSION AND FUTURE OUTLOOK

In conclusion, the plasmonic FBG-based sensor is a promising candidate for food security applications with regard to its outstanding properties, such as simple structure and high sensitivity. The recent usages of the plasmonic FBG-based sensors cover diverse applications such as thrombin detection, protein detection, smart farming (humidity and temperature detection), glucose detection, heavy metal ions in drinking water detection, salinity monitoring and methane sensing. Among various types of grating structure design, the integration of TFBG with SPR exhibits the most significant fibre optic sensing system with regards to the critical role of the tilted grating is proven able to enhance the sensitivity up to 688 nm/RIU. The combination of spectral

resonances and SPR, obviously results in the excitation of strong evanescent waves that consequently lead to the sensitivity enhancement of the plasmonic-based TFBG sensors in detecting viruses, gases and even low concentrations of contaminants in food and drinking water. Interestingly, the review also concludes that the hybrid structure of MMF-TFBG produced in better sensitivity than SMF-TFBG owing to its large numerical aperture that increases the mode field diameter and the number of propagating modes. This situation causes the generation of stronger SPR signal by MMF-TFBG as the fibre is coated with metal thin film with 18.30 % of the sensitivity improvement. In term of materials, although gold is more expensive than silver, yet it is still the most popular noble metal that has been used to generate a plasmonic effect due to its amazing properties, which are non-oxidised material, strong and chemical resistance. The output of this review suggests the optimised thickness of gold thin film is 35 nm, which the sensitivity of the respected sensor is successfully enhanced up to 70.35 % in comparison with the common thickness of gold (50 nm).

In line with the current concerns on food security issues, we believe the development and innovation of portable, simple and high-sensitivity sensors has become more significant nowadays. Recent works conducted by researchers as discussed in this paper indicates the bright potential of plasmonic-based FBG sensors to be deployed as a great alternative to overcome the related issues. The ability of chitosan in enhancing the sensing performance because of its structural ability proposes new alternative materials to be hybridised with metal thin film. For future prospects, the studies on hybrid materials consisting of gold/graphene oxide/chitosan (Au/GO/CH) coated on TFBG is expected to expand the sensing capability of plasmonic-based optical sensors for food security applications.

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