International Journal of Chemical and Biochemical Sciences
(ISSN 2226-9614)

Journal Home page: www.iscientific.org/Journal.html

Plasmonic Fiber Bragg Grating Sensor for Health Monitoring Applications: Review on Fiber Structures, Material Properties, and Deposition Techniques

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Abstract

For years, technologies in monitoring diseases and sickness for early stages detection have been actively developed. Previously, fiber Bragg Grating (FBG) has been widely used for strain, pressure and temperature sensing. Recently, this type of fiber optics has broadened its application in health monitoring field including cancer and various types of viruses' detection. The combination of surface plasmon resonance (SPR) and propagating cladding modes created by FBG has proved able to enhance the strength of evanescent field in which consequentially increase the sensitivity of FBG sensor. This study reviews the utilization of plasmonic fiber Bragg Grating (FBG) in the health monitoring field in recent years by considering the types of FBG, plasmonic materials, metal deposition techniques and their current applications. In health monitoring application, plasmonic tilted FBG (TFBG) displayed impressive sensing ability resulted from the transmitted light coupling into backward cladding combine with the excitation of surface plasmon polaritons compared to the conventional FBG. These applications include cancer diagnosis, glucose detection, protein detection and respiratory problem. Gold with thicknesses between 30 nm and 50 nm is the most preferable noble metal to generate SPR due to its non-oxidized and chemically stable properties compared to other noble metals. Sputtering has become the most extensively used technique for metal film deposition on FBG because of its ability to create excellent film's adhesion and good thickness uniformity compared to dip coating and spin coating. In conclusion, FBG based SPR sensor technology exhibits bright potential for health monitoring applications due to its simple working procedure, high sensitivity and uncomplicated fabrication process.

Keywords: Fiber Bragg Grating (FBG), Tilted FBG, Optical sensor, Noble metal, Health monitoring

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1. Introduction

A quality and superior health is primary to human happiness and well-being that contributes remarkably to success and wealth and even economic advancement, as healthy populations are more productive. It is a vital responsible for every human to take care of their health from an infant to being an old person. Maintaining health is crucial to be able to play, work, learn and live life the way every person desires. However, there are several diseases that affect human health such as heart problems, skin diseases, respiration issues, and stroke. In 2019, the world's primary killer was ischemic heart disease, accountable for 16% of the world's total deaths. The disease recorded 8.9 million deaths, an increment of more than 2 million since 2000. Runner-up disease was stroke with 11% of total deaths and the third place was chronic obstructive pulmonary disease responsible with 6% of total deaths in the society. In Malaysia, ischemic heart disease was the main primary cause of death with 15% of total death in 2019. Pneumonia disease came behind with 12.2% and in the third place was cerebrovascular disease with 8% of total deaths. Looking at the statistics, it is a crucial duty for humans to pay attention to their health for a longer and meaningful life. For years, monitoring diseases and sickness has been developed for early stages detection. Numerous technologies have been employed such as genetic and proteomic analysis, immune histochemistry and the quantitative polymerase chain reaction "Q-PCR" for cancer detection, electrode method, electrochemical method, colorimetric method and chemiluminescence method for detection of blood glucose and the utilization of electrodes fixed to human's body for monitoring of respiration [1-3]. The disadvantages of these technologies are due to their time-consuming and sometimes prevent patients from moving. The rise in technology of optical fiber has improved in the early-stage detection of human illness problem.

Medical devices have been affinity to be based on optical sensors. To generate surface plasmon resonance (SPR) on the fiber Bragg grating (FBG), physical access to the core-guided light is locally needed so that it can be brought into contact with the surrounding medium of different refractive indices. More modern configurations of FBG photo-inscribe in the fiber core permits light coupling to the surrounding medium. As metal coated FBG brings interest towards the advancement of technology, this is since the SPR-FBG give many benefits such as: (i) tuning of the SPR mode-excitation wavelength via selective mode coupling; (ii) succession on similarity with telecommunication-grade-optical fibers and equipment; (iii) conservation of fiber integrity; and (iv) compatibility with mass production, among others. Therefore, a lot of developments based on SPR excitation have come through nowadays [4]. The combination of surface plasmon resonance (SPR) and propagating cladding modes created by FBG has proved able to enhance the strength of evanescent field in which consequentially increase the sensitivity of FBG sensor. This study was carried out to review and analyze the utilization of plasmonic FBG in the health monitoring field in recent years by considering the types of FBG, plasmonic materials, metal deposition techniques and their recent applications. We believe the output of this study will be able to contribute significantly to the extension work of plasmonic FBG for health monitoring applications.

2. Characteristics of Fiber Bragg Grating (FBG) and Surface Plasmon Resonance (SPR)

2.1. Fiber Bragg Grating (FBG)

Fiber Bragg Grating (FBG) is a type of optical fiber that when there is an intense laser of light, the center of the single-mode fiber (SMF) will be exposed to it in interval of time [5]. Bragg wavelength is all the light reflection signals combine coherently to a large reflection at a particular wavelength when the period of grating is roughly half the input wavelength of light. As the exposure happens, it will create a constant increase in the refractive index of this fiber's core. An unchanged index modulation generates the pattern exposure when the refraction index increased. The Bragg's wavelength is given by:

$$\lambda_{Bragg} = 2n\lambda \qquad (1)$$

In equation (1), n is the refractive index of the FBG and λ is the period of the index of refraction variation of the FBG. The FBG structure depends on its grating period and refractive index. There are various kinds of grating periods which can be graded or uniform, and either distributed or localized in an FBG. For the refractive index, it has two prime features which are the offset and profile. The refractive index profile can be changed either uniform or apodised while the refractive index can be zero or positive. There are six ordinary structures of FBG such as uniform positive-only index change, Gaussian apodised, raised cosine apodised, chirped, discrete phase shift and superstructure. FBG is made up of silica (glass) that is only millimeter in type of length which can be classified as small and very light in weight [6]. It resists electromagnetic interference (EMI) and even lightning interference. FBG has very high stabilization in the long term and is a passive intrinsically device which does not require any electrical power to turn it on. Therefore, this type of fiber optics can be placed in a very high voltage place or capably in areas with explosive atmosphere and has a very good resistance to corrosion. **Figure 1** lists the advantages of FBG sensors.

2.2. Principle of Surface Plasmon Resonance (SPR)

A plasmon is a quasiparticle created by electrons on a metal surface. A plasmon dispersed on a metal surface is known as surface plasmon [7]. Gold, silver and copper are among the favorable materials that have been used to generate plasmonic signal due to their ability to create strong oscillation of electrons [8-10]. The plasmon condition, SPR is the resonant oscillation of conduction electron at interface that can help to generate evanescent wave which results from the plasmonic reaction between the atoms on the metal and the fiber surfaces. When this occurs, the efficiency for the sensor becomes higher thus, the sensing properties of the plasmonic is stronger. The incidence and characteristics of SPR sensitivity are affected by the wavelength of photon, metal type, angle of incidence illumination, thicknesses of metallic layer and the optical properties of dielectric materials above the metallic layer. Based on these characteristics, SPR can be used as a sensor to detect various optical properties in dielectric specimens on a metallic surface. SPR is monitored by the refractive index (RI) changes of a medium by measuring resonance angle shifts, or wavelength of resonance in the output signal.

To generate SPR, there are two approaches that recently have been used, which are free space -based by using prism coupling and fiber optics-based. For the prism coupling approach, there are two types of configurations that can be employed to generate SPR, namely Kretschmann configuration and Otto configuration as illustrated in **Figure 2.** In Kretschmann configuration, noble metal thin film is directly deposited on top of the prism's hypothenuse side. The metal thickness is controlled to achieve SPR [11]. In contrast, the air gap thickness is manipulated to generate SPR in Otto configuration. Kretschmann configuration is preferable due to its practicality and obviously it is easier to control the thickness of thin metal film than controlling the air gap. Nanomaterials have received great attraction in the field of biosensors due to their impressive sensitivity in chemical and biological sensing. In localized SPR, gold nanoparticles with diameter size between 30 nm to 50 nm are the most favorable among the nanomaterials because of their stability, and large enhancement ability of the local electromagnetic field. Other than prism coupling, fiber-based approach is an alternative to generate SPR. In terms of application, the fiber-based approach is more practical for various types of applications due to its compact size and simple operating procedure. **Figure 3** illustrates the example of fiber optics-based SPR by coating the cladding part of fiber optics with gold nanoparticles to generate localized SPR.

3. Applications of Plasmonic Based FBG Sensor in Health Monitoring

In health monitoring applications, the plasmonic based FBG sensors have been widely used for various detection such as cancer, protein, glucose and in respiratory system as illustrated in **Figure 4**. This review mainly focuses on these types of applications by taking into consideration the monitoring techniques, type of materials and sensor's sensitivities.

3.1. Cancer diagnosis

Early detection of cancer is critical because after several diagnosis some type of cancers can lead to stroke, in which a big role leads to death. There are more than 100 types of cancer and usually they are named by the tissues or organs. For example, brain cancer starts from brain cells, breast cancer begins from breast cell, and lung cancer starts from lung cells. Therefore, early detection of cancer cells is very crucial. Various studies of optical device sensors including tilted Fiber Bragg Grating (TFBG) have been developed for trouble-free cancer detection at early stages by recognizing biomarkers. Ribaut et al. proposed an optical sensor that can detect cytokeratin 7 (CK7), a protein-based by utilizing 50 nm gold coated tilted fiber Bragg grating (TFBG) which was tilted at 7º angle [1]. Immobilization receptor, AbCK7 was used for binding agents to study the sensitivity of two different CK7. A year later, this research group tested the CK17 in buffer, gel matrix and human tissue using the same previous design of TFBG [12]. It was found that there was a shift about 0.147 dB at high concentration of gel with BSA 1 x 10^{-6} g/mL. The biosensor then was tested in human tissue resulting to 0.61 dB within 10 min with limit of detection (LOD) was 1 pM. The proposed biosensor successfully detected the presence of positive CK17 in situ for in-vitro diagnosis. Loyez et. al. proposed 7º angle TFBG coated with ~50 nm gold film by phase-mask technique on the surface, a label-free detection for cytokeratin. They came up with an idea of three functionalization processes for the immobilization of antibodies. These processes were tested in PBS and CK17 solutions with different concentrations [13].

Caucheteur et. al. proposed <10º of TFBG bare, coated with ~5 nm and ~35 nm gold nanoparticles and 35 nm electroless plating (ELP) for CK17 detection. For ~5 nm and ~35 nm gold coated TFBG, a clear polarization was obtained with p-polarized modes. ELP was used to optimize the gold coating thicknesses. The results indicated that the usage of 35 nm gold nanoparticles exhibited higher surface refractive index (SRI) sensitivity with ~55 nm/RIU, meanwhile 5 nm gold nanoparticles produced the sensitivity value about ~33 nm/RIU. The maximum sensitivity was obtained when the diameter of gold nanoparticles was set about ~35 nm as it resulted the highest amplitude variation with LOD 10^{-12} g/mL [14]. Lobry et. al. (2020) conducted an experiment utilizing 1 cm long of 7º TFBG to produce cladding modes with effective RI coated with ~35 nm gold nanoparticles for HER2 detection [15]. This study deployed two types of fibers, multimode fiber-tilted fiber Bragg Grating (MMF-TFBG) and single mode fiber-tilted fiber Bragg grating (SMF-TFBG). The output of their study shows the gold-coated MMF-TFBG exhibited higher sensitivity with 124.89 nm/RIU than gold-coated SMF-TFBG with 102.03 nm/RIU. The introduction of aptasensor for HER2 detection, a biomarker of breast cancer by utilizing 35 nm gold coated TFBG shows impressive sensing performance [16]. Note that aptasensor is the biosensor that recognized the element and strain of DNA and RNA aptamers. The wavelength red shift of ~300 pm was observed during the interactions of HER2 protein, but then the wavelength shift rose to ~800 pm, a very high sensitivity by utilizing anti-HER2 antibodies.

Recently, Li et al. reported the development of SPR biosensor using FBG fused with multimode fiber (MMF) for lung cancer gene detection with temperature and pH compensation [37]. In this study, the SPR was generated by coating the FBG part with 30 nm thickness of gold thin film. The FBG part then was fused with the multimode fiber (MMF) before connected to the light source and optical spectrum analyzer (OSA). The most interesting part of this research was due to the capability of this sensor to detect lung cancer gene of epidermal growth factor receptor (EGFR) gene and other parameters which are temperature and pH value, simultaneously with maximum sensitivity of 0.04 nm/nM. The combination of photonic crystal fibers (PCF) and fiber Bragg grating technology become one of the new alternatives for label-free biodetection of HER2 by utilizing cladding mode resonance [39]. Interestingly, straight FBG was fabricated in the PCF which make it a very compact device with multifunction application. Gold thin film with thickness up to ~ 40 nm was deployed as plasmonic material to generate SPR by injecting light source with wavelength range between 1480 to 1640 nm. This sensor was able to detect down to 1 μg/mL of HER2 concentration.

3.2. Respiratory System

Respiration is the frequency of human breathing per minute. Human respiration needs to be monitored regularly to observe whether the amount of air entering and leaving the lungs is sufficient. Lacking oxygen in human blood can causes parts of human body do not receive the required oxygen thus they will not function properly which is called hypoxemia. Hypoxia is another term concern on lacking oxygen in the human tissue [17]. Besides lacking in lung oxygen, viruses spread between humans through respiratory droplets, direct and indirect contacts and fine particle aerosols causes respiratory virus infection [18]. There are many laboratory tests have been conducted to detect these respiratory viruses such as adenovirus, human metapneumovirus, influenza virus, Newcastle Disease Virus (NDV Virus) and the latesr one, Novel Coronavirus Disease 2019 (COVID-19). Many viruses can be detected through respiratory system. Therefore, for healthy respiration purpose, researchers introduced various types of sensors to observe the respiration rate. Vital signs of breathing sensor based on FBG had been presented by Krej et. al [19]. The analysis was based on FBG signals of strain, heartbeat and thorax measurement from breathing action. The measurement was tested at 1510 nm to 1590 nm wavelength. It needed to be noted that during the MRI scanning, there were 30% of patients with fluctuation in breathing. The highest sensitivity was 100% recorded by, and the lowest sensitivity was only 94.74% recorded by 9th person while the other was on average reading. Next, respiratory detection based on graphene had been reported by Pang et. al [20]. As respiratory was closely related to humidity, the proposed sensor was flexible, light and highly conductive porous graphene network by combination of CVD growing graphene on the nickel foam and chemical dealloying utilizing hydrochloric acid. Surface of GO also been modified with PEDOT: PSS and AC to improve the sensitivity and response time. Porous graphene/AC displayed the highest sensitivity of 0.0321 with the best linearity of 0.985. Fajkus et. al. introduced a sensor probe consisted of two FBG surround with polydimethylsiloxane polymer (PDMS) [21]. This experiment utilized Fourier series analysis to analyse a series of periodic waveform of respiration. The proposed sensor was able to monitor up to 128 vital signs in a single time.

The recorded time for the individuals all were difference range between 8 minutes 30 seconds (individual 6, female) until 23 minutes 45 seconds (individual 2, male. The mean respiratory rate was in the range between 13.9 rpm to 19.0 rpm, with the total average mean was 16.22 rpm. The result showed 96.54% of the values detection lied within ±1.96 standard deviation (SD). Jiang et al. proposed graphene oxidase (GO) film with thicknesses ~54 nm deposited on the Tilted Fiber Grating (TFG) [22]. GO has the property of powerful absorption in broad range of wavelength besides has high surface area to volume ratio. GO also can be utilized as UVA and biochemical sensor because GO can be easily integrated with optical fiber. As human breathing had a lot of water vapors, the resonant dip wavelength shift resulted to the lower power of transmission. This sensor was tested with two different breathing frequencies: normal respiration rate and fast respiration rate. The frequency for the normal respiration was 0.7 Hz meanwhile for the respiration rate was 1.1 Hz. The sensitivity of this GO-TFG was 0.0185 nm/%RH. For virus detection, many sensors also have been developed based on SPR-FBG. Newcastle disease virus (NDV) has led to abundant of dead in various types of birds. For humans, the virus can cause some flu-symptoms and infection to eyes like conjunctivitis also causes swelling of the voice-box area, laryngitis. Luo et al. proposed an optical sensor in monitoring NDV virus which was excessively tilted fiber gratings (Ex-TFG) coated with ~80 nm thicknesses of gold nanosphere [23].

Result showed that there was a wavelength shift occurred when immersed in the solution. The response time increased as the NDV concentrations become higher. The sensitivity was ~1.627 pm/(pg/mL) and the detection limit was ~25 pg/mL. Dengue also a virus carried by mosquitoes can affected the respiratory system. A person who is infected with dengue virus will eventually has rapid breathing during the critical phase. Omar and her co-workers laid out an idea application of SPR based on optical sensor [24]. The immobilization of monoclonal antibody (IgM) on a thin of gold layer/Fe-MPA-NCC-CTAB/EDC-NHS. IgM solutions with concentrations ranging from 0.0001, 0.001, 0.01, 0.1, 1, 10 nM and 10 nM were prepared. Result showed the sensitivity of SPR optical sensor was 39.96^{o} nM^{-1}. The newest virus, COVID-19 struck the world has become dangerously widespread virus that killed about 1.8 million people worldwide. Samavathi and co-workers proposed a COVID-19 sensor based on SPR-FBG [25]. The sensor consisted of 30 nm GO-functionalized Au coated on FBG with hydrocarbon chains as the immobilization material to detect COVID-19 virus in which had been tested onto 4 male and 2 female patients with three different stages: early infection phase, pulmonary phase and hyperinflammatory phase., Hydrocarbon chains were deployed as immobilization material to detect COVID-19 virus. Wavelength and detected light intensity were modulated for 0.39 nm and 0.48 dB, respectively after 10 s of the sensor exposed to the probe and this experiment continued until 1600 s. 10 s of exposure resulted to 0.4250 x 10^{-8} nm/virus number meanwhile the sensitivity for 1600 s was 0.0833 x 10^{-8} nm/virus number. This showed that the higher the exposure time towards the virus, the lower the wavelength sensitivity. Higher density virus led to thicker layer of GO resulting significant changed in SRI and amplitude in terms of virus quantity. The hyperinflammatory phase recorded 0.92 nm wavelength shift and 1.68 dB amplitude change while early infection phase was 0.39 nm and 0.48 dB respectively. Yang et al. introduced Ta_2C-MXene /Au/TFBG biosensor for detecting SARS-CoV-2 Omicron by using broadband light source in the wavelength range between 1520–1603 nm [38]. In this study, the tilt angle of FBG was set at 8◦. Interestingly, the deployment of Ta_2C-M on Au-TFBG resulted in higher surface energy polarization density of states and signal transduction capacity in comparison with the absence of these materials. This biosensor exhibited better sensitivity than RT-PCR test, which was under receiver operating characteristic curve, ROC = 1.

4. Glucose Detection

Blood glucose is the amount of sugar in blood obtained from the food human eat. Blood glucose has the recommended level for human to control to ensure the person is free from hyperglycemia. Hyperglycemia is glucose or sugar level is higher than normal level in the blood occurs when the body does not produce enough insulin that led to diabetes, an illness that can cause many health problems. Primarily, 50 nm gold coated with optical fiber with the covalent binding of glucose oxidase (GOD) for glucose sensor had been presented by Zheng and co-workers [2]. Enzymatic reaction between GOD and glucose caused RI change which led to wavelength shift on SPR spectrum. The sensor was tested to various glucose concentrations ranging from 0 to 1.2 mg/mL. It was found that as the concentration GOD increased, the maximum shift of wavelength shifts subsequently decreased. This analysis proved the concentration of GOD has its limit for the optimization of SPR shift spectrum. The result illustrated the sensor can achieved high SPR sensitivity of 85.4 (mg/mL) for glucose solution between the concentration of 0 to 0.5 mg/mL. The usage of FBG for glucose sensor had been proposed by Jiang and colleagues which was GOD functionalized on 82^{o} angle tilted fiber grating (TFG) in favor of detection low concentration of glucose [26]. β-D-glucose solutions with different concentrations ranging from 1mM to 10 mM were prepared for this experiment. The wavelength shifted by 8.85 nm due to the high RI of the coating. Ranging from 0 to 8 mM concentrations of glucose, the sensor's sensitivity was obtained as ~0.24 nm/mM. The sensor showed high SRI sensitivity which was ~128 nm/RIU with the sensor's length of 12 mm and presented good glucose sensitivity happened at 0.24 nm/mM ≈1.33 nm/(mg/ml). Yuan et. al. developed 50 nm gold coated a multimode optical fiber (MOF) for glucose sensor and glucose sensitive membrane (GSM) with immobilization of GOD and SiO_2 nanoparticles [27]. When the glucose concentration in the region was 0.80 mg/dL, the wavelength shift became lower approximate linearly and the sensitivity was 0.14 nm/(mg/dL). SPR-TFBG coated with 35 nm of gold thin film has been proposed by Lobry and co-workers in detection of non-enzymatic D-glucose stereoisomer [28]. D-glucose is a type of glucose sugar which is necessary for the human body. D-isomer is the prime saccharide in human blood digested by the cells for adenosine triphosphate (ATP) manufacturing which is the source of energy for living organisms. D-glucose SPR-TFBG has been functionalized with polydopamine-immobilized concanavalin A. Reference in PBS showed 108 pm wavelength shifts in the 10^{-2} M D-glucose concentration. SPR shift displayed 3.83 ± 0.05 nm in 20 minutes.

Zhang et. al. developed an optical sensor which plasmonic material, silver film was deposited on the 18° angle of TFBG [29]. A 32 nm of silver film was coated onto the fiber by using magnetron sputtering coating machine, meanwhile glucose concentration was varied between 0 mM to 12 mM in serum solution. The SPR-TFBG was then immersed in H_2O_2 solution with refractive index was between 1.32 and 1.34. The silver coated-TFBG was immersed in each different concentration of glucose solutions for 20 minutes. Instead of monitoring the wavelength shifted, they monitored the rate of attenuation change in the SPR. The change of amplitude during this duration was obtained as 1500 nm. This proposed sensor resulted in 0.05 dB/mM sensitivity in the span of 20 minutes. Luo et. al. proposed the optical sensor consisted of excessively tilted fiber grating (eTFG) engraved in thin-cladding optical fiber (TCOF) coated with glucose oxidase (GOD) immobilization for glucose concentration detection [30]. The immersion of the proposed sensor into the solution resulting to the glucose convert to gluconic acid, which was higher molecular weight that led to very large change in the refractive index (RI) even in the dilute solution. This caused a more notable change in RI between the cladding and caused a remarkable resonance wavelength shift. The sensor experiment was repeated a few times to observe an average red-wavelength shift of ~ ± 0.2nm. The sensor had a more remarkable wavelength red shift of the sensor. The sensitivity for this sensor was ~1380 nm with the refractive index range between 1.345 to 1.370.

5. Protein Detection

Protein plays an abundance of roles in the human body so that the body can function properly. Protein carries out most jobs in cells and is essential for structure, function and regulation of the body’s tissue and organs. Researchers have proposed various optical sensors in detection of glycoprotein. Glycoprotein is a chain of protein and carbohydrate molecules that participate in various physiological functions such as immunity. Thrombin is a class of protein which reacts as an enzyme for coagulation of blood. The proposed sensor by Sypabekova et al was 50 nm size of gold nanoparticles coated on 10° tilted angle of TFBG with phenylboronic acid derivative (PBA) loaded on the sensing region as a receptor molecule while thrombin molecule of different concentrations as the target [31]. The observed wavelength had the maximum sensitivity of 3.3 pm/mM. The sensitivity of the proposed sensor increased from 1.25 nm/RIU to 23.38 nm/RIU as the etching time increased. Other thrombin detection based on SPR-FBG was titanium dioxide (TIO_2) functionalized on 16 nm of Au coated long period gratings (LPG) by Coelho et. al. [32]. The sensor was incubated in several concentrations of thrombin ranging from 10 to 100 nM for affinity of thrombin for 1 hour and was tested in different RI solutions between 1.335 to 1.430. Sensitivity towards SRI recorded was 3100 nm/RIU. The thrombin detection was achieved with 0.9 nm wavelength shift and 0.54 nm resolution with value of sensitivity between 0.35 nm/nM to 0.025 nm/nM. Albert and coworkers demonstrated SPR based TFBG for thrombin binding aptamer detection using gold thin film with thicknesses between 30 nm to 50 nm as plasmonic material [33]. The sensor was tested to the protein buffer, the targeted solution with different concentrations for 20 minutes. As thrombin was added into the different SRI solution, the proposed sensor exhibited a fast wavelength shift in the first 10 minutes and SPR shift happened. ~ 500 nm/RIU of SRI sensitivity was recorded in the SRI range of 1.32 to 1.42. Next, Jiang et. al. investigated the detection of protein molecules by utilizing SPR-TFBG for fast real-time detection of protein [34]. IgG antibody aqueous solution was used in this experiment to attract protein molecules to the sensor. Cysteamine hydrochloride solution was used to shift the SPR wavelength to the larger ones. For 1 mol cysteamine hydrochloride solution, 0.03 nm wavelength shifted while for 2 mol solution, 2.23 nm wavelength was shifted. The resonance peak wavelength was obtained at 5.2 nm for IgG antigen-antibody hybridization experiment using the proposed SPR-TFBG sensor. Protein in urine is another significant indicator to determine human health. Note that normal human urine is lower than 150 mg / 24 h and if more than that, this will lead to proteinuria. If someone has proteinuria, it will result in kidney failure and renal disease. Guo et. al. proposed a SPR-TFBG for detection of urinary protein [35]. They introduced three types of TFBG such as bare TFBG, 20-30 nm Ag coated on FBG and 50 nm Ag coated on 20º TFBG. These FBGs were then tested on three groups of rats which were a healthy group of rats, a sick group of rats injected with Adriamycin and a treated group of rats injected with Adriamycin and Zhen Wu Tang medicine with RIs 1.3400, 1.3405 and 1.3408, respectively. SPR wavelength shift can be easily achieved with high accuracy measured for 50 nm SPR-TFBG based on p-polarized by monitoring the amplitude change. The 50 nm SPR-TFBG displayed the coupling of cladding mode energy (near 1490 nm) and very lousy surface plasmon wave was maximized at this thickness. The SPR-TFBG exhibited high sensitivity of 5.5 dB/(mg/ml) with LOD 1.5 X 10^{-3} mg/ml.

5.1. Analysis of Plasmonic Fiber Bragg Grating Sensor for Health Monitoring Applications: Fiber Structures, Material Properties and Deposition Techniques

Table 1 presents the summary of recent studies in health monitoring applications detected by plasmonic based FBG sensors. Based on this review, it can be concluded there are several types of FBG have been used for health monitoring applications such as conventional FBG, TFBG and eTFBG. Their applications include cancer diagnosis, respiratory system, glucose detection and protein detection. Since the substrate is a glass fiber optics, the preferable operating wavelength is 1550nm (infrared laser) to avoid large light attenuation. Obviously, 50nm thickness of gold thin film is the most preferable plasmonic material to generate SPR due to its stability and non-oxidation properties. Note that, at this optimum thickness, maximum excitation of surface plasmon polaritons have been successfully generated. If the film is too thick, part of the SPR signal will be absorbed by the film itself which limits the percentage of incident light to be converted into SPR. Meanwhile, the usage of a very thin film of noble metal will result the electrons damping issue [36]. For the thin film deposition, sputtering is the most favorable technique due to its simple process and easily to control the thin film’s thicknesses. **Figure 5** displays the analysis of recent studies on the usage of plasmonic FBG in health monitoring applications based on **Table 1**. 40% of the FBG based plasmonic sensors have been used in cancer diagnosis, meanwhile 25% of the applications are focused on the protein detection.

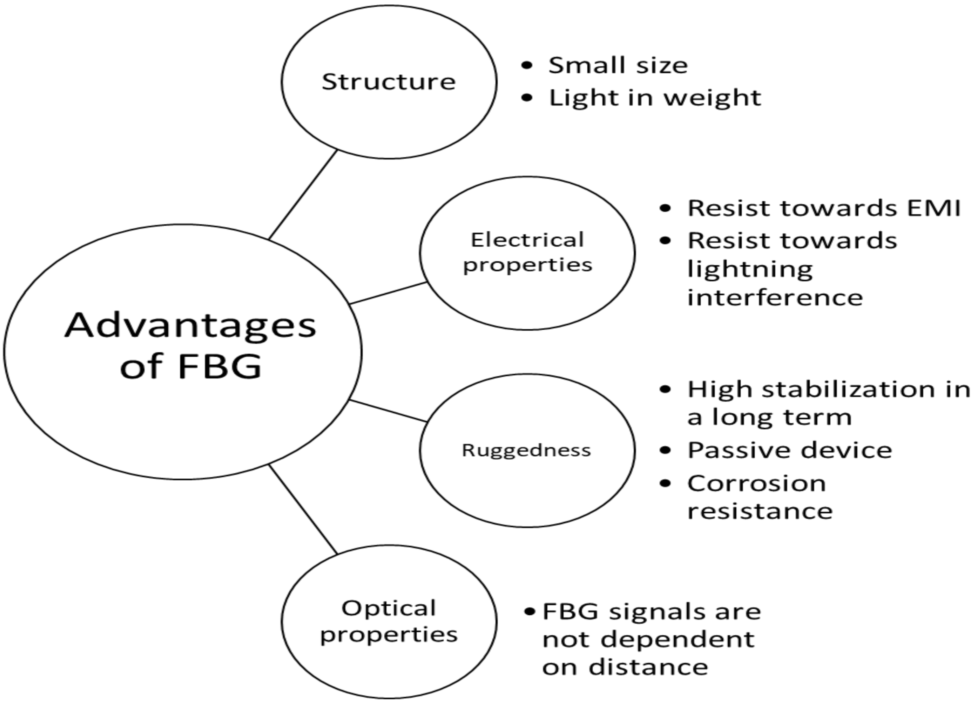

Figure 1. The advantages of FBG sensor.

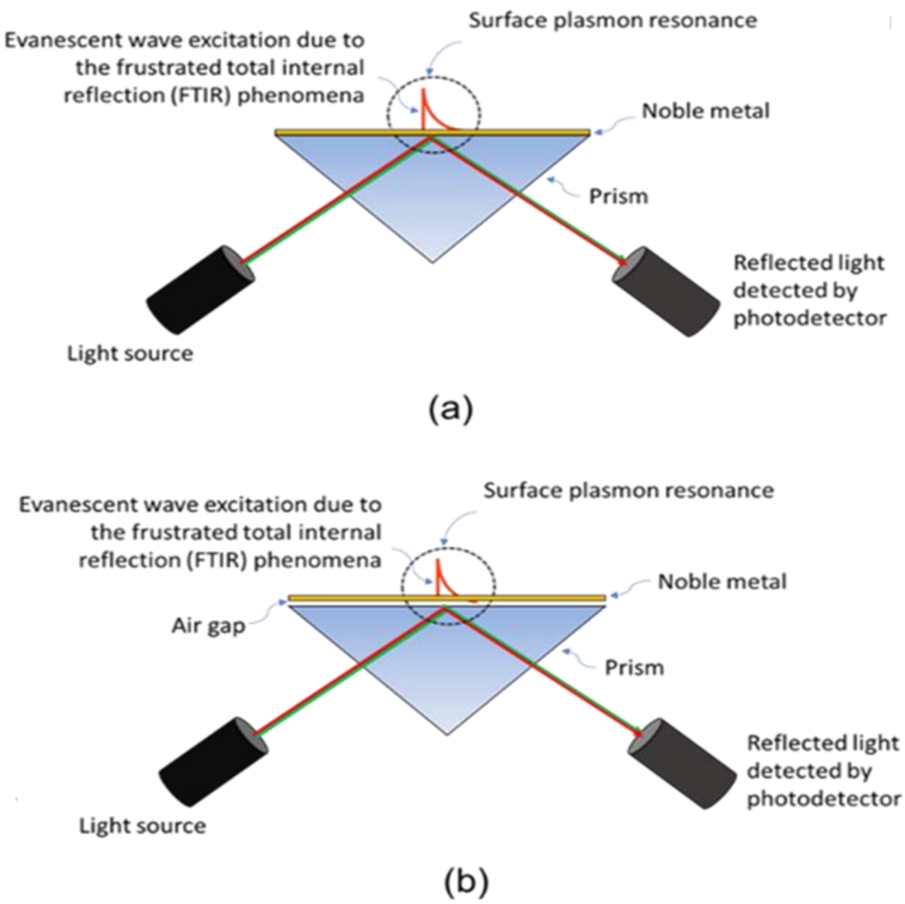

Figure 2. Two types of SPR setup to generate SPR (a) Kretschmann configuration (b) Otto configuration.

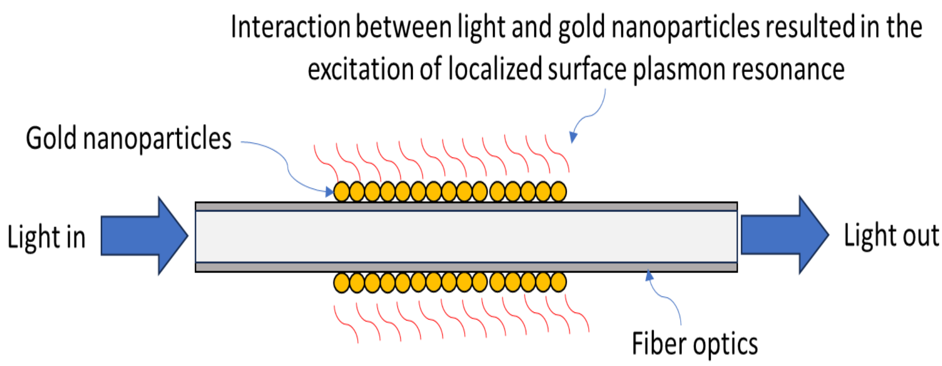

Figure 3. Excitation of localized SPR as light propagated inside the fiber optics experiences total internal reflection and interacts with gold nanoparticles.

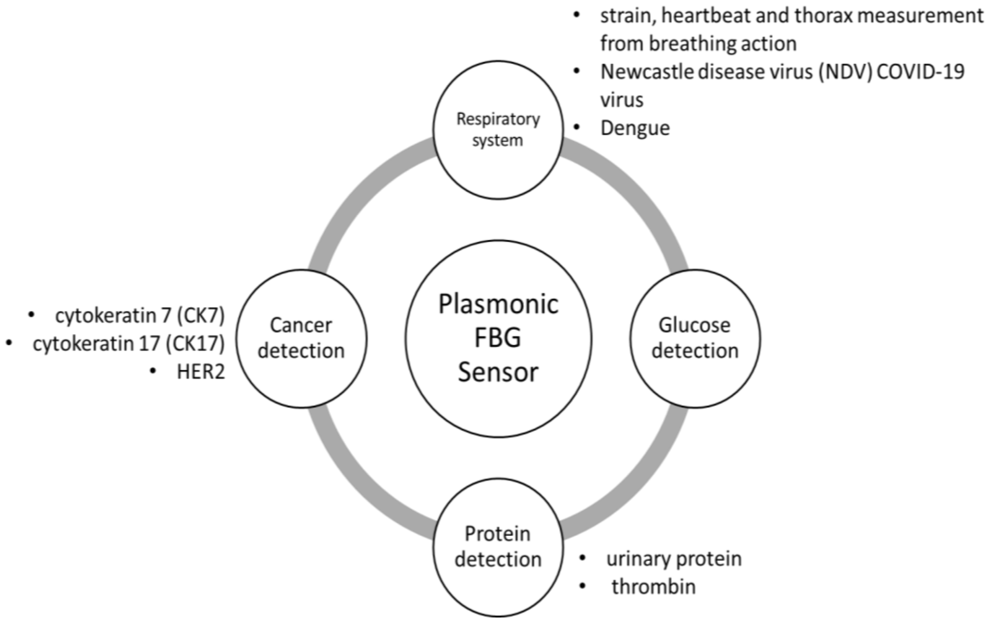

Figure 4. Recent applications of plasmonic based FBG sensors for health monitoring.

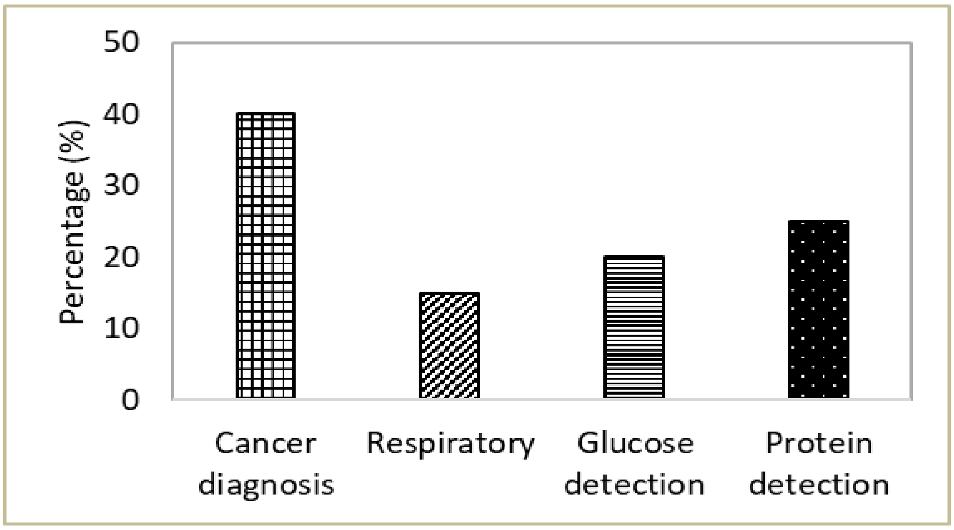

Figure 5. Various applications of plasmonic FBG in health monitoring.

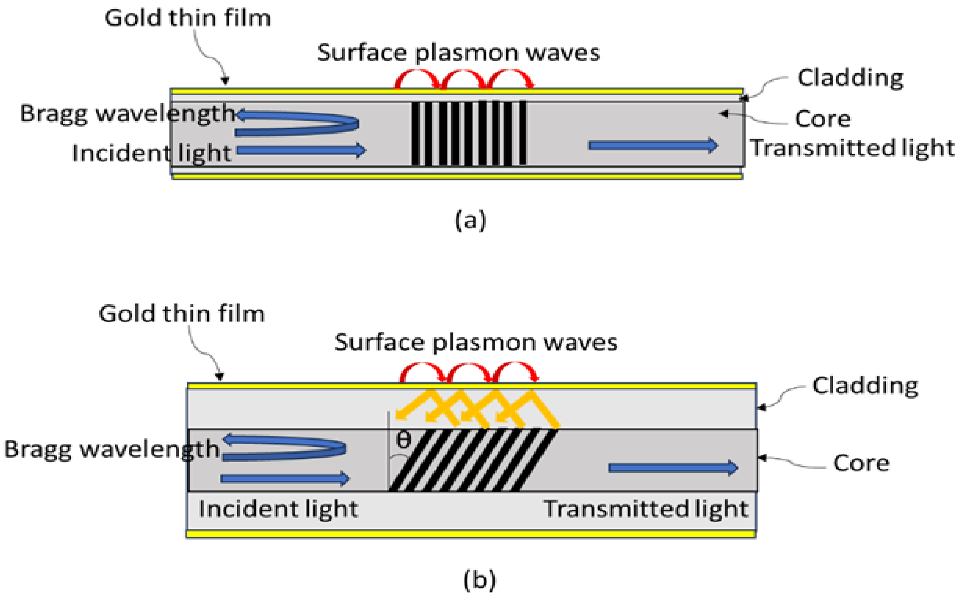

Figure 6. Basic physical structure of plasmonic based sensor (a) FBG (b) TFBG.

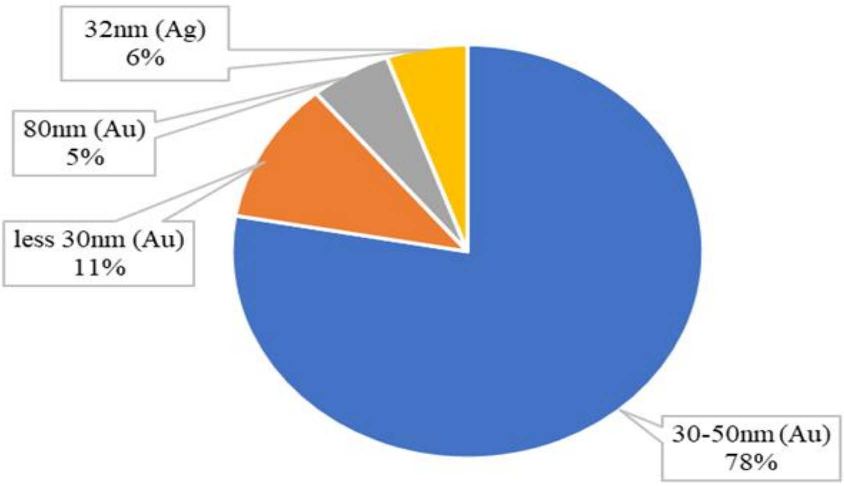

Figure 7. Types of plasmonic materials with various thicknesses coated on FBG for health monitoring applications.

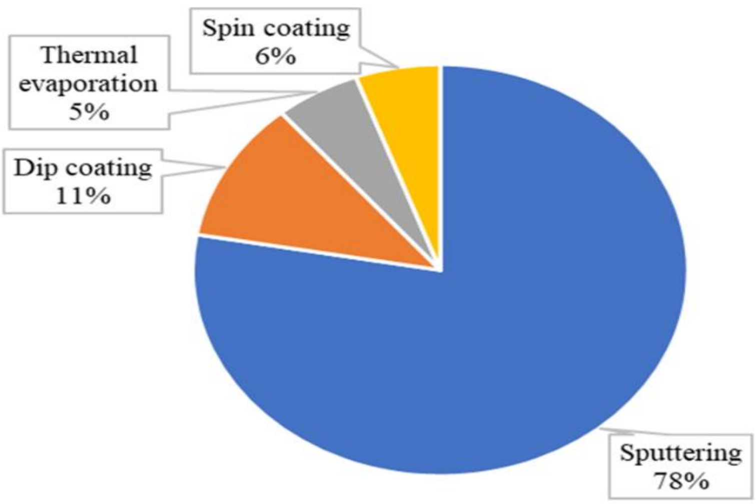

Figure 8. Various types of metal deposition techniques used to develop plasmonic FBG sensor for health monitoring application.

Table 1: Summary of recent works on health monitoring using various types of FBG by utilizing SPR phenomena.

Application	Type of Application	Types of Fiber Optics	Plasmonic Material (Thicknesses)	Light Wavelength	Technique of Coating	Immobilized Material/ Analyte	Sensitivity	Ref.
Cancer Diagnosis	Cytokeratin-17 biomarker	TFBG	Gold (50 nm)	IR (1500-1600 nm)	Sputtering-coating Technique	Anti-CK17	2.5 dB	[1]
		TFBG	Gold (~50 nm)	IR (1500-1600 nm)	Sputtering-coating technique	Anti-CK17	-	[13]
		TFBG	Gold (~5nm & ~35 nm)	IR (1500-1600 nm)	Sputtering-coating technique	Anti-CK17	35nm-~55nm/RIU ~5nm-~33nm/RIU	[14]
		TFBG	Gold (~50 nm)	IR (1500-1600 nm)	Sputtering-coating technique	Anti-CK17	Shift to 1.5 dB at 1×10^{-10} g/mL	[12]
	HER2 biomarker	TFBG	Gold (35 nm)	IR (1500-1600 nm)	Sputtering-coating technique	Anti-HER2	~800 pm (wavelength shift)	[16]
			Gold (35 nm)	IR (1500-1600 nm)	Sputtering-coating technique	Anti-HER2	1. SMF-TFBG - 102.03 nm/RIU 2. MMF-TFBG- 124.89 nm/RIU	[15]
		PCF-FBG	Gold	IR (1480 to 1640 nm)	Sputtering-coating technique	Anti-HER2	Minimum detection: 1 µg/mL of HER2 concentration	[39]
	eGFR gene exon-20	FBG	Gold (30nm)	Visible to NIR (500-100 nm), IR (1546-1552 nm)	-	pDNA	0.04 nm/nM	[37]
Respiratory System	Respiration	FBG	-	1510 ~1590 nm	-	-	94.74%-100%	[19]
		Porous Graphene Network	Graphene (15 nm)	-	-	-	0.0321	[20]
		FBG	-	1500 ~1600 nm	-	-	96.54%	[21]
		GO-TFBG	Graphene (~54 nm)	1490 ~ 1570 nm	Dip-coating Technique	-	0.0185nm/%RH	[22]
	Virus (NDV)	ExTFG	Gold nanosphere (~80 nm)	1510 ~1590 nm	-	Anti-NDV MAbs (SPA)	~1.627 pm/(pg/mL)	[23]
	Virus (Dengue E-protein)	SMF	Gold thin film	632.8 nm (HeNe laser)	Spin Coating Technique	IgM	39.96^{0} nM^{-1}	[24]
	SARS-CoV-2	GO-decorated Au-FBG	Gold (30 nm)	1547 nm	Sputtering Coating Technique	Hydrocarbon chains	1. 1600 s - 0.0833×10^{-8} nm/virus number 2. 10 s	[25]

							- 0.4250 x 10^{-8} nm/virus number	
		Ta_2C-M-Au-TFBG	Gold thin film	1520–1603 nm	-	SARS-CoV-2 Omicron BA	ROC = 1	[38]
Glucose Detection	-	SMF	Gold (50 nm)	360 nm-2000 nm	Sputtering Coating Technique	GOD	85.4 (mg/mL)	[2]
	-	TFG	-	-	-	GOD	1. SRI - ~128 nm/RIU 2. Glucose - 0.24 nm/mM ≈1.33 nm/(mg/ml)	[26]
	-	MOF	Gold (50 nm)	360-1200 nm	Dip-coating Technique	GOD and SiO_2	0.14 nm/(mg/dL)	[27]
	-	TFBG	Gold (35 nm)		Sputtering Coating Technique			[28]
	-	TFBG	Silver (32 nm)	1500 – 1600 nm	Magnetron Sputtering Technique	GOx	0.05 db/mM	[29]
	-	eTFG	-	-	-	GOD	~1380 nm	[30]
Protein Detection	-	TFBG	Gold (50 nm)	1500 – 1600 nm	Sputtering Coating Technique	Aptasensor	3.3 pm/mM	[31]
	-	FBG	Gold (16 nm)	1500 – 1550 nm	Thermal evaporation	TIO_2	0.35 nm⁄nM - 0.025 nm⁄nM	[32]
	-	TFBG	Gold (30 to 50 nm)	1500 – 1600 nm	Sputtering Coating Technique	Aptamer	~500nm/RIU	[33]
	-	TFBG	Gold	1526 – 1560 nm	-	IgG	5.1 nm	[34]
	-	TFBG	Silver (20 to 50 nm)	1440 – 1550 nm	Magnetron Sputtering Technique	-	5.5 dB/(mg/ml)	[35]

This sensor exhibits excellent selectivity in differentiate different types of analytes which make it suitable to be used as biosensors to distinguish various types of viruses including coronavirus (Covid19). Apparently, with the assistance of SPR phenomena, more evanescent waves able to be generated in which simultaneously enhanced the sensitivity of the sensor in detecting the CK17, CK7, HER2 and SARS-CoV-2. Apparently, the TFBG based SPR sensor is more preferable than the conventional FBG for health monitoring application with percentage of usage about 73%. Note that, to generate a significant SPR signal, it is important to create frustrated total internal reflection so that strong evanescence field able to be established [40]. To achieve this condition, the most common technique that has been utilized is by reducing the cladding part as thin as possible so that the core part will be very close to the medium to be detected as shown in **Figure 6 (a).** These techniques include etching and mechanical polishing [41-42]. As the light interact with the gold thin film, surface plasmon resonance will occur resulted in the introduction of sensing properties of the fiber. Thicker cladding diameter will prevent light to interact with plasmonic material (gold, silver etc) and subsequently the surface plasmon polaritons unable to be generated. Another alternative to produce evanescent wave is by bending the fiber optics including FBG [43]. By controlling the fiber bending radius, the evanescence waves can be generated. However, the main challenge for those mentioned techniques are the fragility issue where the fiber optics are easily to break. In TFBG, grating planes are blazed at an angle with respect to the fiber-propagating axis; as such, light transmitted in the fiber couples with the core mode as well as backward-propagating cladding modes, leading to a series of dense spectral resonances as shown in **Figure 6 (b)** [44]. This condition provides special advantage of TFBG compared to FBG due to its ability to couple the transmitted light into backward cladding without weaken the physical strength of the fiber itself [45]. In fact, a complicated fabrication process to establish strong SPR based on FBG technology also can be avoided by using TFBG.

The utilization of noble metal as part of sensing material distinguish the major difference between plasmonic sensor and other optical sensors. **Figure 7** depicts the percentage of materials that has been used to generate plasmonic effect from FBG for health monitoring applications. Undeniably, gold is the most preferable noble metal with percentage of usage up to 94%; to generate SPR using FBG-based sensor for health monitoring application. Meanwhile, only 6% of application used silver as alternative material to generate SPR. The properties of gold that non-oxidized and chemically stable make it the most favorable material to excite surface plasmon polaritons and consequentially become the best candidate in developing high sensitivity sensor [46]. 78% of the recent research deploys gold thin film or nanoparticles within 30 nm to 50 nm thickness or diameter size respectively. In term of practicality, the deposition technique at this range of thickness is more controllable because it is less difficult to produce uniform thin film layer. As the thickness decreases below 30 nm, one of the main challenge is to ensure the uniformity of the metal layer. Note that the SPR signal is mainly affected by the film thicknesses or nanoparticle's diameter size. If the film is too thick, light will be absorbed by the metal itself and contingently avoid the excitation of plasmon polaritons. Conversely, too thin of film thickness will result electron damping that will limit the occurence of SPR [47]. Materıal deposition technique is one of the crucial approach to ensure strong adherence of metal on the substrate. Sputtering is the most preferable technique with 78% of utilization to deposit metal on FBG as shown in **Figure 8**. It is one of the most extensively used techniques metal film deposition on FBG. This technique offer several advantages, such as low processing temperature, good film's adhesion, good thickness uniformity and high density of the films. Technically, the process parameters such as working pressure, substrate temperature and sputtering power are easy to control [48]. The dip coating and spin coating techniques require liquid material to execute these processes. In localized SPR, these techniques are used for metal nanoparticles deposition. It is noteworthy to highlight the importance of solution's viscosity to ensure the adherence of nanoparticles on FBG. Seed-mediated growth is one of the popupar synthesis technique to produce metal nanoparticles such as gold nanoparticles and silver nanoparticles due to its simple process and does not require high-end equipment. However, it is difficult to control the viscosity of the solution since this synthesis process focuses on the dimension of nanoparticles, not the solution condition. Therefore, we believe this is one of the main reason why only small percentage of works use dip coating and spin coating deposition technique.

6. Conclusions

This study reviews the utilization of plasmonic FBG in health monitoring field in recent years by considering the types of FBG, plasmonic materials, metal deposition techniques and their recent applications. In comparison with conventional FBG, the plasmonic TFBG sensors have been extensively used for cancer detection because of their high sensitivity in detecting CK7, CK17 and HER2. The main advantage of plasmonic TFBG compared to the conventional FBG due to its impressive sensing ability resulted from the transmitted light coupling into backward cladding combine with the excitation of surface plasmon polaritons. Undeniably, in FBG-based sensor technology for health monitoring application, gold is the most preferable noble metal to generate SPR due to its non-oxidized and chemically stable properties compared to other noble metals. Until today, sputtering is the most extensively used technique for metal film deposition on FBG because of its excellent film's adhesion and thickness's uniformity. We believe the output of this study able to contribute significantly to the extension.

Acknowledgement

The Faculty of Science and Technology (FST), Universiti Sains Islam Malaysia (USIM) is acknowledged for the research facilities.

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