Sensors and Actuators B 193 (2014) 467–471

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

General

High-sensitivity sensing based on intensity-interrogated Bloch surface wave sensors

Weijing Kong[a], Zheng Zheng[a,*], Yuhang Wan[a], Shuna Li[a,b], Jiansheng Liu[a]

[a] School of Electronic and Information Engineering, Beihang University, 37 Xueyuan Rd, Beijing 100191, China
[b] National Key Laboratory for Electronic Measurement Technology, North University of China, 3 Xueyuan Rd., Taiyuan, Shanxi 030051, China

ARTICLE INFO

Article history:
Received 28 August 2013
Received in revised form
22 November 2013
Accepted 25 November 2013
Available online 2 December 2013

Keywords:
Bloch surface waves
Optical sensor
Surface plasmon resonance
Label-free
Biosensor

ABSTRACT

A high-sensitivity sensing scheme based on Bloch surface wave is presented with the simple intensity interrogation configuration. The p-polarized electromagnetic surface wave is designed to be excited in a one-dimensional photonic crystal band-gap structure, and support a rather steep resonance dip, much sharper than that of the well-known surface plasmon resonance (SPR). Although the angular shift of this Bloch-surface-wave-based sensor is not as sensitive, the intensity measurement proves to be a more suitable scheme for Bloch surface wave based sensors, thanks to the sharpness of their resonance. Through detection of glycerol in water solution for different concentrations, the intensity sensitivity of our Bloch-surface-wave-based sensor significantly surpasses that of the conventional SPR-based sensors. Experimental results show that the sensor could achieve a detection limit as low as 7.5×10^{-7} refractive index units in a simple lab setup, which is much simpler than many of the much more complicated SPR-based platforms.

1. Introduction

Surface waves are the electro-magnetic waves that propagate along the interface between two media and can be strongly confined and significantly enhanced at the surface and decay exponentially into the neighboring media. They have been studied and demonstrated in many photonic application areas, among which sensing methods based on surface waves have become powerful diagnostic tools due to their unique properties, such as high surface sensitive, real-time and label-free detection. The most popular surface-wave-based sensing technology is undoubtedly the surface plasmon resonance (SPR) method. The phenomenon of SPR occurs by the excitation of the surface plasmon wave (SPW) along a metal/dielectric interface. When the incident beam's wavevector matches that of the SPW's, light is coupled into the relatively lossy SPW. In the widely used prism coupling configuration, an angular- or wavelength-dependent resonance response can be observed. Because of the high sensitivity of such resonance conditions to the material properties at the interface, the SPR technology has emerged as the 'gold standard' for label-free biomolecule interaction analysis [1,2].

Nevertheless, its sensitivity, 10^{-5}–10^{-6} RIU in terms of detection resolution for most lab demonstrations [3], is still dwarfed by many labeled sensing methods like the fluorescence-based ones. Besides many other factors, the sharpness of the resonance response for SPR is limited. For example, normally, its angular intensity curve has a width on the order of 1°. Thus, the sensitivity for the popular angular and intensity interrogation schemes is limited as well. Although different methods and more complicated interrogation configurations, like phase detection, have been explored to alleviate the problem, the efforts to further improve the sensitivities of the SPR-based biosensors are hampered by these fundamental constraints set by the SPR effect itself. Investigation of other types of sensors such as metal-clad waveguides showed that their much sharper resonances could be very helpful in enhancing the detection performance [4,5]. While interferometric waveguide sensors [6], on the other hand, could realize very high sensitivity due to their long interaction length, planar sensors, similar to SPR devices, are still very attractive for many biosensing applications because of their simplicity to fabricate and to realize multi-channel systems.

On the other hand, Bloch surface wave (BSW) is another kind of surface electro-magnetic waves that bear some similar characteristics with SPW but possess some distinctly different features as well [7]. BSW is usually excited in photonic band-gap (PBG) structures, for example made up of truncated periodically alternating dielectric layers [8,9], and propagates along the interface between dielectrics. Therefore, it is much less lossy compared to SPW, which could result in very sharp resonance curves. Similar to what's demonstrate in [4,5], as another alternative to their SPR counterparts, the use of all-dielectric, BSW-based sensors could lead to improved sensing performance, even under comparable

* Corresponding author. Tel.: +86 10 82317220.
E-mail address: zhengzheng@buaa.edu.cn (Z. Zheng).

0925-4005/$ – see front matter
http://dx.doi.org/10.1016/j.snb.2013.11.101

sensitivities. Besides, the photonic band-gap can be carefully designed by picking the right materials and structure dimensions. Therefore, the excitation of the BSW could be realized over a very wide range of wavelengths and for different polarizations, which offers much greater flexibility comparing with SPR. In lieu of the success of SPR technologies, there have been more and more interests to adopt the BSW effect as a potential alternative for biosensing applications [10–16].

Besides the previous works in chemical sensing using the properties of Bragg reflection or the photonic stop band [17–19], the excitation of the BSW in the PBG structure has been demonstrated experimentally [10–12], and many interesting physical phenomena associated with BSW, such as giant Goos-Hanchen effects, have been explored [20–22]. Several label-free biosensing schemes based on BSW sensors had been explored [13–16]. Many of the above studies are based on the wavelength interrogation scheme, and the detection limit shown had been on the order of 8×10^{-6} RIU [14]. A resolution of 10^{-4} RIU is reported recently based on the angular interrogation scheme for detection of protein [15], which is orders of magnitude lower than that of the angular interrogation of SPR sensors [3]. Comparison between the BSW and the SPR-based sensors shows that the SPR-based resonance dip is always wider and deeper than the BSW based one due to the high loss of the metal layer. The angular shift of the SPR sensor is usually larger than the BSW sensor as well, which leads to a better sensitivity in angular interrogation and explains the better performance of the SPR system working in the angular interrogation mode. However, although the BSW based resonance dip is not as deep as the SPR's, its slope could be much steeper due to the much sharper resonance curve. Therefore, the intensity interrogation scheme, which is arguably the simplest one among the common choices, could be a more suitable scheme for the sensing systems based on BSW sensors, where the intensity changes measured are due to the shift of the resonance dip. It has been demonstrated that the BSW sensors are able to compete with the SPR sensors with intensity sensitivity [23]. Despite of that, experimental demonstration of good detection resolution has not been easy. The best detection limit experimentally reported so far with the method of intensity interrogation is 3.6×10^{-6} RIU [24].

In this paper, through particularly design of the PBG structure, an extremely sharp resonance peak is experimentally observed, and high intensity-interrogation sensitivity is present. Our results show that an intensity sensitivity of 156 RIU^{-1} that significantly surpasses the conventional SPR sensor's is achieved and a detection limit of 7.5×10^{-7} RIU is obtainable even under a simple direct detection setup, which outperforms the previous results of BSW-based similar sensing schemes.

2. Sensor structure and experimental setup

In our scheme, a specially designed PBG slab that could support BSW for water ($n = 1.33$) is evaporated on a ZF10 ($n = 1.668$) glass substrate to form the basic sensor structure. The PBG structure is designed for the *p*-polarized incident beam at the wavelength of 980 nm. It is made up of 20 alternating layers of TiO_2 ($n = 2.30$) and SiO_2 ($n = 1.434$), with the designed thicknesses of 163 nm and 391 nm, respectively, where the last layer in this periodical structure that adjacent to the external medium is a 500 nm-thick SiO_2 layer. Fig. 1 shows the band structure of an infinite one-dimensional PBG structure calculated using the formula in [25], where the materials and the parameters are the same as those listed above. The blue region represents the allowed band, and the red region is the forbidden band. The light lines for water and air are plotted as well. For the incident wavelength of 980 nm, the rising edge of the forbidden band is just to the left of the light line for water, which makes it easy for the excitation of BSW for aqueous applications. Also, the position of the BSW mode excited is shown as the circle in the plot. Its position can be observed through the angular-dependent reflectance of the designed PBG structure, as shown in Fig. 2, which is calculated using the Fresnel equations [9]. The absorption coefficient of TiO_2 is assumed as 2×10^{-4} in calculation to account for the possible scattering loss at the interfaces as well as the intrinsic material loss. By plotting the position of the BSW mode in the band structure (Fig. 1), it can be seen that the BSW mode falls within the band-gap and lies below the light line for water, ensuring that the mode is sufficiently confined at the surface, similar to the case of the SPR sensing. Fig. 2 plots the calculated reflectance curve of the PBG structure based on the parameters given above, when the external medium is water for a *p*-polarized input. It shows that the BSW mode can be excited beyond the critical angle. The FWHM of the corresponding resonance dip is 0.01° and the minimum reflectance is 0.47. The calculated normalized distribution of the magnitude of electronic field for the surface mode is shown in the inset, showing that the electrical field vector could be strongly confined and enhanced at the surface and exponentially decays into the neighboring area of the material to be sensed, similar to the surface plasmon wave.

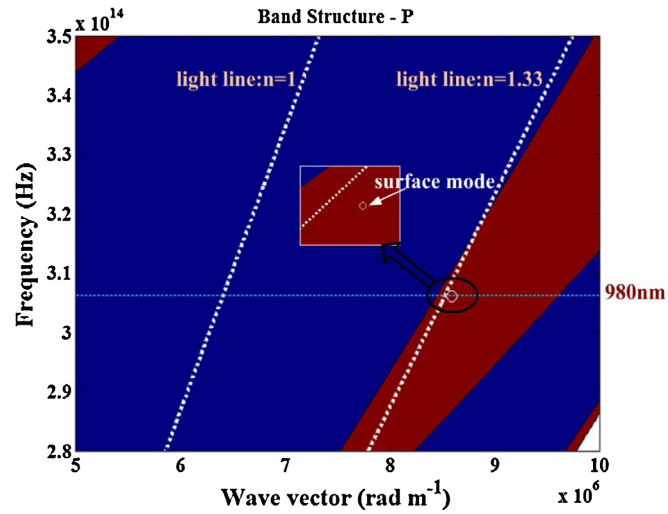

Fig. 1. Band structure of the 1D PC structure for the p-polarization light.

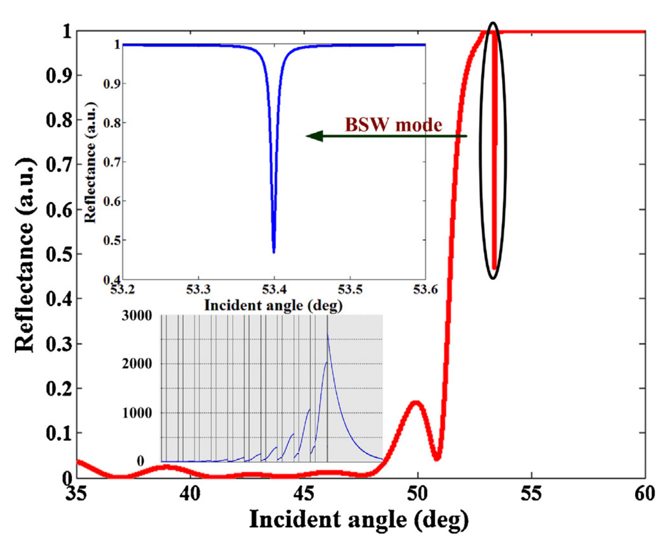

Fig. 2. Simulated angular-dependent reflectance of the designed PBG structure when the external medium is water for p-polarization. Inset: field distribution for the BSW mode.