Highly Sensitive Grating-coupled Bloch Surface Wave Resonance Bio-sensor via Azimuthal Interrogation

V. Koju*[1], W. M. Robertson[1,2]
[1]Computational Science Program, Middle Tennessee State University, Murfreesboro, TN 37132, USA [2]Department of Physics and Astronomy, Middle Tennessee State University, Murfreesboro, TN 37132, USA
*Corresponding author: vk2g@mtmail.mtsu.edu

Abstract: A dielectric multilayer structure, with a grating profile on the surface layer, can couple light into a strongly confined surface wave, known as a Bloch surface wave. These surface modes can be used to design bio-sensors. The corrugated surface structure also enables azimuthal angular excitation of Bloch waves. . In this paper, we exploit azimuthal interrogation to design highly sensitive Bloch surface wave bio-sensors. We present finite-element based numerical simulations to show enhanced refractive index sensitivity.

Keywords: Bloch surface wave, Grating coupling, Bio-sensors, Dielectric multilayer, Azimuthal interrogation.

1. Introduction

Bloch surface waves (BSWs) are electromagnetic excitation modes that exist at the interface of truncated dielectric multilayer structures and a homogeneous medium. Although BSWs are intrinsically present at such interfaces, they cannot be directly excited by light incident from the homogeneous medium due to their non-radiative and evanescent nature [1]. The use of a grating coupler or a prism mitigates this inability by providing an additional momentum to the free-space wave vector required to satisfy the phase matching condition with the BSW wave vector. Here we present a new highly sensitive sensing technique based on grating-coupled Bloch surface wave resonance (GCBSWR) via azimuthal control.

Since GCBSWR bio-sensors do not require a bulky prism to couple light into BSWs, they are strong candidates for nanoscale bio-sensors. But conventional GCBSWR bio-sensors, based on either wavelength or angular interrogation, are observed to be less sensitive compared to prism-coupled Bloch surface wave resonance (PCBSWR) bio-sensors [2]. However, due to their inhomogeneous surface architecture, GCBSWR bio-sensors can be interrogated by rotating the grating platform azimuthally. We exploit this ability to improve the sensing capability of GCBSWR bio-sensors.

2. Use of COMSOL Multiphysics® Software

We use COMSOL® Multiphysics 5.2a with the RF module for the simulations in this paper. The RF module solves for the electric and magnetic fields from Maxwell's vector wave equation

$$\nabla \times \mu_r^{-1}\left(\nabla \times \vec{E}\right) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)\vec{E} = \vec{0}, \quad (1)$$

where $k_0 = \omega\sqrt{\mu_0\varepsilon_0}$ and the symbols have their usual meanings. In our study however, $\mu_r = 1$, $\varepsilon_r = n^2$, and $\sigma = 0$. Eqn. (1) thus reduces to

$$\nabla \times \left(\nabla \times \vec{E}\right) - k_0^2 n^2 \vec{E} = \vec{0}, \quad (2)$$

where n is the refractive index of the material. We consider wavelength dependent refractive indices for TiO_2 [3] and SiO_2 [4] as the high and low refractive index materials given by

$$n_{TiO_2} = \left(5.913 + \frac{0.2441}{\lambda^2 - 0.0803}\right)^{\frac{1}{2}} \quad (3)$$

and

$$n_{SiO_2} = \left(1 + \frac{0.6962\lambda^2}{\lambda^2 - 0.0684^2} + \frac{0.4079\lambda^2}{\lambda^2 - 0.1162^2} + \frac{0.8975\lambda^2}{\lambda^2 - 9.8961^2}\right)^{\frac{1}{2}}. \quad (4)$$

λ in Eqn. (3) and (4) are in the units of μm. In the rest of the paper however, λ is given in nm.

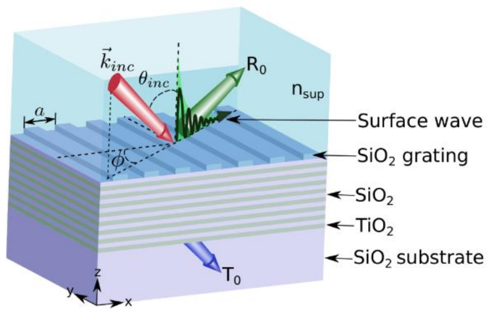

Figure 1. Schematic of a grating coupling technique to excite Bloch surface waves on the surface of a dielectric multilayer.

We consider a three dimensional dielectric multilayer structure, with a grating profile on the surface layer, as shown in Figure 1. The TiO_2 and SiO_2 layers have thicknesses of 126.12 nm and 205.41 nm respectively. The excitation and confinement of Bloch surface waves on the surface of a one dimensional photonic crystal is highly sensitive to the thickness of the surface defect layer due to the effects of multiple reflections from the periodic dielectric multilayer beneath. For this reason, we set the thickness of the top SiO_2 layer to 280.03 nm. The grating height is set to 70 nm with a fill out factor of $0.5a$ where a is the grating period set to 510 nm. The refractive index of the superstrate layer considered in our study is 1.26-1.4. The polar incident angle (θ_{inc}) is measured relative to the surface normal, while the azimuthal angle (φ) is measured with respect to the plane perpendicular to the grating profile. The incident wavevector $\overrightarrow{k_{inc}}$ has component magnitudes

$$\begin{aligned} k_x &= k_0 sin(\theta_{inc}) cos(\varphi), \\ k_y &= k_0 sin(\theta_{inc}) sin(\varphi), \\ k_z &= k_0 cos(\theta_{inc}). \end{aligned} \quad (5)$$

The problem is modeled using Floquet boundary conditions on the sides of the domain and Port boundary conditions at the top and bottom.

3. Results

We first look at the reflection response of our 16 layered TiO_2-SiO_2 dielectric multilayer structure, with a grating profile on the surface layer, for the azimuthal angle $\varphi = 0^\circ$. The reflection response as a function of wavelength and incident angle is shown in Figure 2. At around the wavelength range of $620 - 680\ nm$ and incident angle range $0^\circ - 10^\circ$, we can see an optical mode. This mode is the BSW mode generated from the grating coupling technique. This mode is a leaky BSW mode because it lies in the radiative region. The quality factors of the BSW resonances in this mode however are high enough to be effectively used for bio-sensing applications.

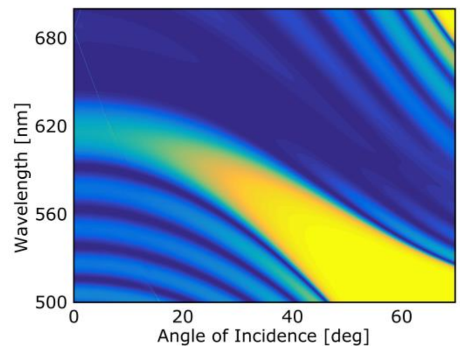

Figure 2. Reflection map of a 16 layered dielectric multilayer structure with a grating profile on the top surface as a function of incident angle and wavelength for azimuthal angle $\varphi = 0^\circ$.

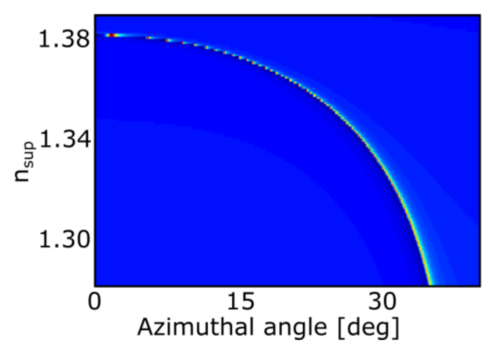

Figure 3. Reflection map of a 16 layered dielectric multilayer structure with a grating profile on the top surface as a function of refractive index of the superstrate layer and azimuthal angle. The incident angle and wavelength are fixed at 5.8° and $632.8\ nm$ respectively.

We implement our structure in COMSOL® Multiphysics as a three dimensional model. Since the structure contains linear grating on the surface layer, the reflection response of the structure depends both on the polar incident angle and the azimuthal angle. The reflection response as a function of the polar incident angle (see Figure 1) is commonly studied. In this paper, we investigate the reflection response as a function of the azimuthal angle instead. Figure 3 shows the reflectivity map as a function of the refractive index of the superstrate layer (n_{sup}) and the azimuthal angle, keep the wavelength and incident angle fixed a $632.8\, nm$ and 5.8°. The superstrate refractive index range in our study is $1.28 - 1.38$. We observe that the slope of the mode decreases as n_{sup} increases. The decreasing slope here indicates that the refractive index change sensitivity increases at higher n_{sup}. The refractive index change sensitivity (S_n) is defined as

$$S_{n_{sup}} = \frac{\Delta\varphi}{\Delta n_{sup}}. \quad (6)$$

The larger the change in the resonance azimuthal angle of BSWs as a function of n_{sup}, the higher the sensitivity of the structure to the changes in the superstate/analyte layer. The maximum sensitivity that we observe is $\sim 1200\,°/RIU$, which is about an order high compared to the conventional polar angular sensitivity.

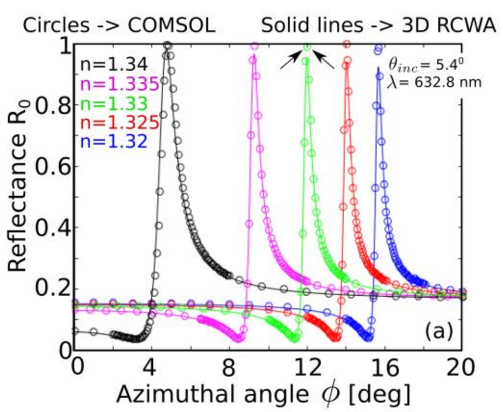

Figure 4. Reflectivity curves as a function of azimuthal angle for different superstrate-layer refractive indices. The wavelength of operation and incident angle are $632.8\, nm$ and 5.4° respectively.

Figure 4 shows the azimuthal reflectivity curves for different values of superstrate refractive indices. We can see a larger shift in the BSW resonance angle as the refractive index increases. It also compare our numerical results from COMSOL® Multiphysics to that from a three dimensional scattering matrix based rigorous coupled wave analysis method (3D RCWA). The results from both the methods are in good agreement.

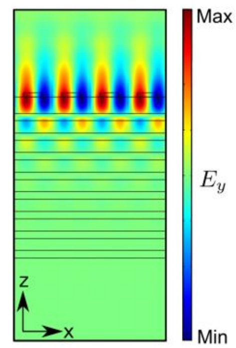

Figure 5. Electric field (E_y) profile of BSW resonance at the wavelength of operation and incident angle $632.8\, nm$ and 5.4^0 respectively. The azimuthal angle is 12°.

The y-component electric field (E_z) profile of BSW at $\theta_{inc} = 5.4^{\circ}$, $\lambda = 632.8\, nm$, and $\varphi = 12^{\circ}$ is shown in Figure 5. The electric field intensity on the surface of the structure at BSW resonance is highly amplified and has an exponential decay profile on the either side of the structure surface.

4. Conclusions

In conclusion, we numerically show that grating coupled BSWs in dielectric multilayer structures can be used to enhance the refractive index change sensitivity via the azimuthal angular interrogation.

5. References

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