Highly sensitive biosensors based on grating coupled Bloch surface waves

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Introduction

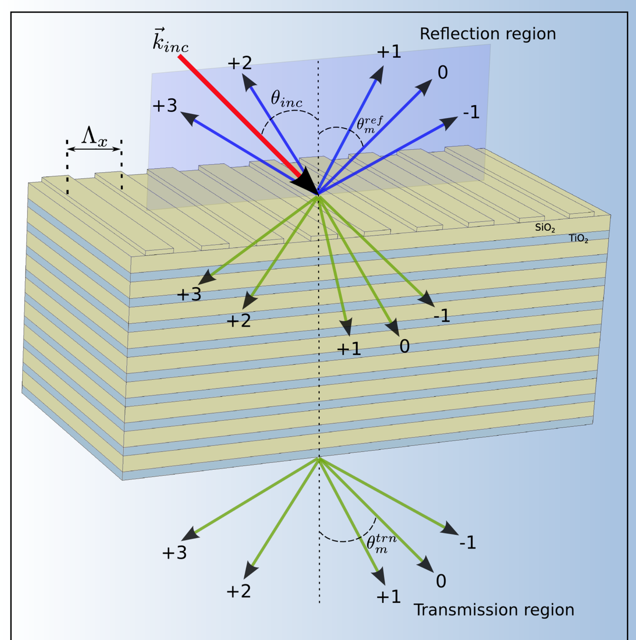

Figure 1. A schematic diagram of dielectric multilayer structure with grating for Bloch surface wave generation

Ability of photonic band gap multilayer films to couple light into strongly confined surface wave, known as Bloch surface wave (BSW), can be exploited to design highly sensitive biosensors. We present finite element based numerical simulations of Bloch surface waves in such multilayer structures with enhanced electromagnetic field intensity at the interface between the top layer of the multilayer structure and air. We use grating coupling, as opposed to a more conventional prism coupling technique, to excite the surface mode. The use of grating coupling offers a number of advantages. First, it significantly reduces the size of the biosensor as it eliminates the need to attach a bulky prism on the device. Second, several Bloch surface modes can be generated by a single carefully designed grating layer on the multilayer structure. We further explore relations between different parameters of the multilayer structure such as angle of incidence, operating wavelengths, and refractive index of incident medium to optimize the sensitivity of the multilayer based biosensor. Finally, to validate our numerical simulations, we compare our results with the results from other widely used numerical techniques such as rigorous coupled wave analysis, and finite difference frequency domain method.

Mathematical Formulation

- Light propagation in dielectric multilayer structure with grating is governed by Maxwell's equations.

$$\Delta \times \mu_r^{-1}(\Delta \times \vec{E}) - k_0^2\left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0}\right)\vec{E} = \vec{0}$$

$$\vec{E}(x,y,z) = \tilde{E}(x,y)e^{-jk_z z}$$

- Analytical solution for the multilayer structure with grating is not available. Thus a rigorous numerical (e.g. Finite Element Method) or semi-analytical (e.g. Rigorous Coupled-Wave Analysis) method that solves Maxwell's equations without any generalization is required to get the solution.

- Due to the presence of graing period on the surface of the multilayer structure, diffraction of light into different diffraction orders occur as shown in Figure 1. The diffraction angles can be found by the momentum matching condition given below.

$$k_0 sin(\theta_{inc}) \pm mk_g = k_{BSW}$$

- Howerver, in order to find the intensities of diffracted orders and field distributions, Maxwell's equations have to be solved rigously over the whole computational domain.

Multilayer with one grating period

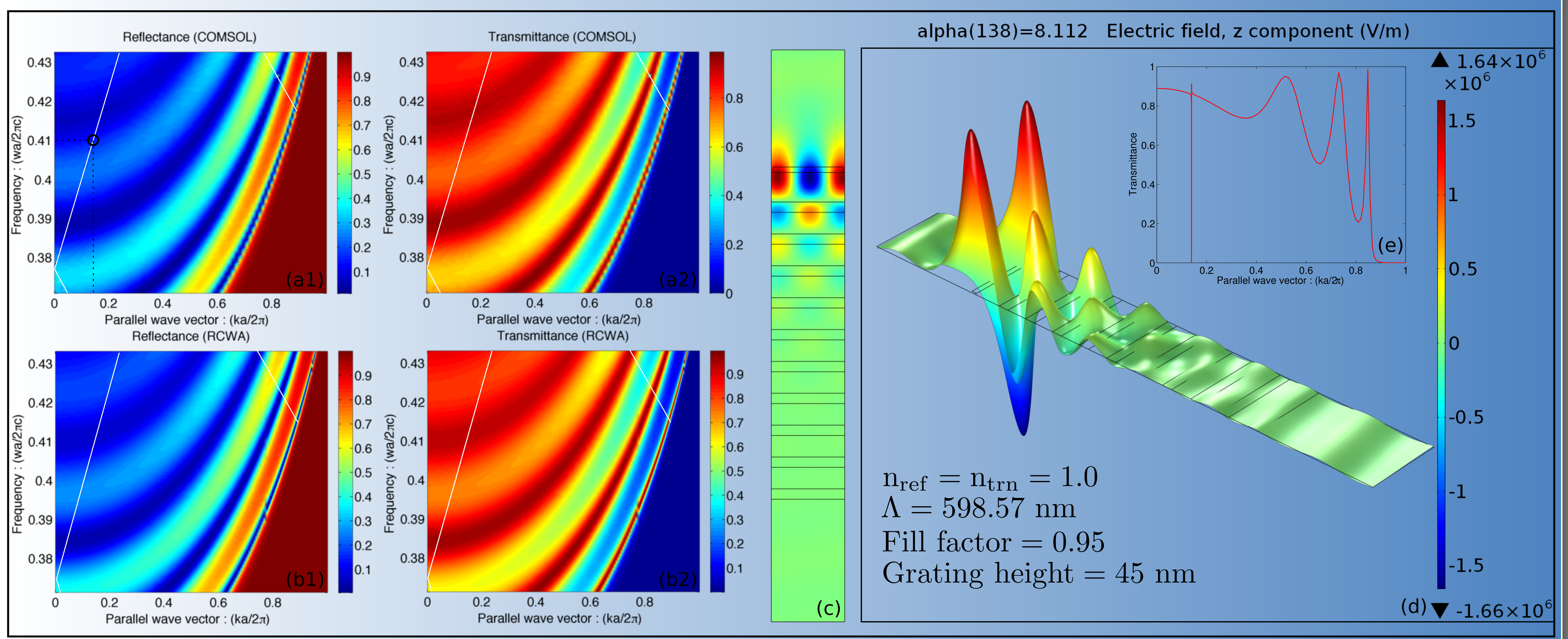

Figure 2.

- (a1) , (b1) Reflectance and (a2) , (b2) transmittance of the TiO_2-SiO_2 multilayer with grating as a function of frequecy and parallel wave vector using COMSOL and RCWA respectively. Results from both the method agree with eathother. The slanted white solid lines represent the Bloch surface wave modes at different incident angles and frequencies.

- (c) , (d) Bloch surface wave generation at a particular frequency of 4.7376e14 Hz and incidence angle of 8.112 degrees denoted by the solid black circle in the reflectance plot (a1). Electric field is highly enhanced at the location (surface) of BSW generation which can introduce non-linear effects. The non-linear effect is used for applications such as second harmonic generation and Raman scattering.

- (e) Transmission response of the device as a function of angle for a specific frequency of 4.7376e14 Hz. A sharp and skinny dip in the transmitted field can be seen at the normalized wave vector of 0.1411 which corresponds to the incidence angle of 8.112 degrees. This property can be used to make higly sensitive biosensors.

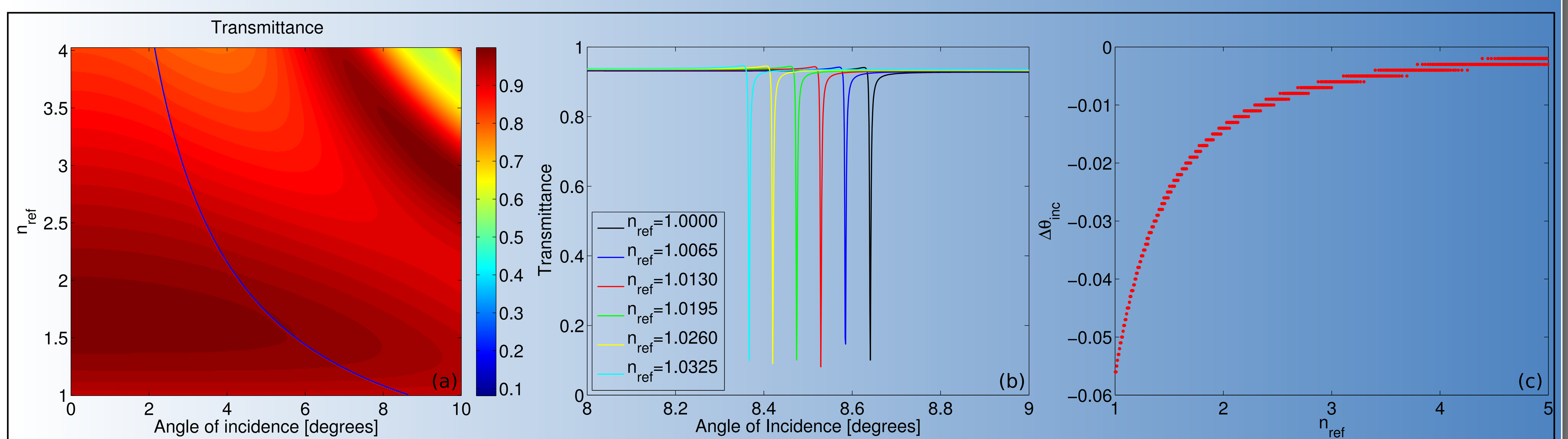

Figure 3.

- (a) Transmittance of the TiO_2-SiO_2 multilayer with grating as a function of refractive index of the incident/reflection region and incidence angle. The solid blue curve represents BSW modes at different refractive index and incident angle.

- (b) Transmission response of the device as a function of incident angle at different refractive indices of the reflection region. This change in refractive index can be viewed at addition of different protein molecules to be studied. Due to the change in the refractive index the location of the transmission dip shifted by a small angle.

- (c) Angular shift in BSW generation due to the change in the refractive index of the incident medium. The rate of angular shift is observed to be high at lower refractive indices, which signifies that the angular sensitivity of the sensor is higher to lower refractive indices. The sensitivity gradually decreases for higher refractive indices.

Multilayer with two grating periods

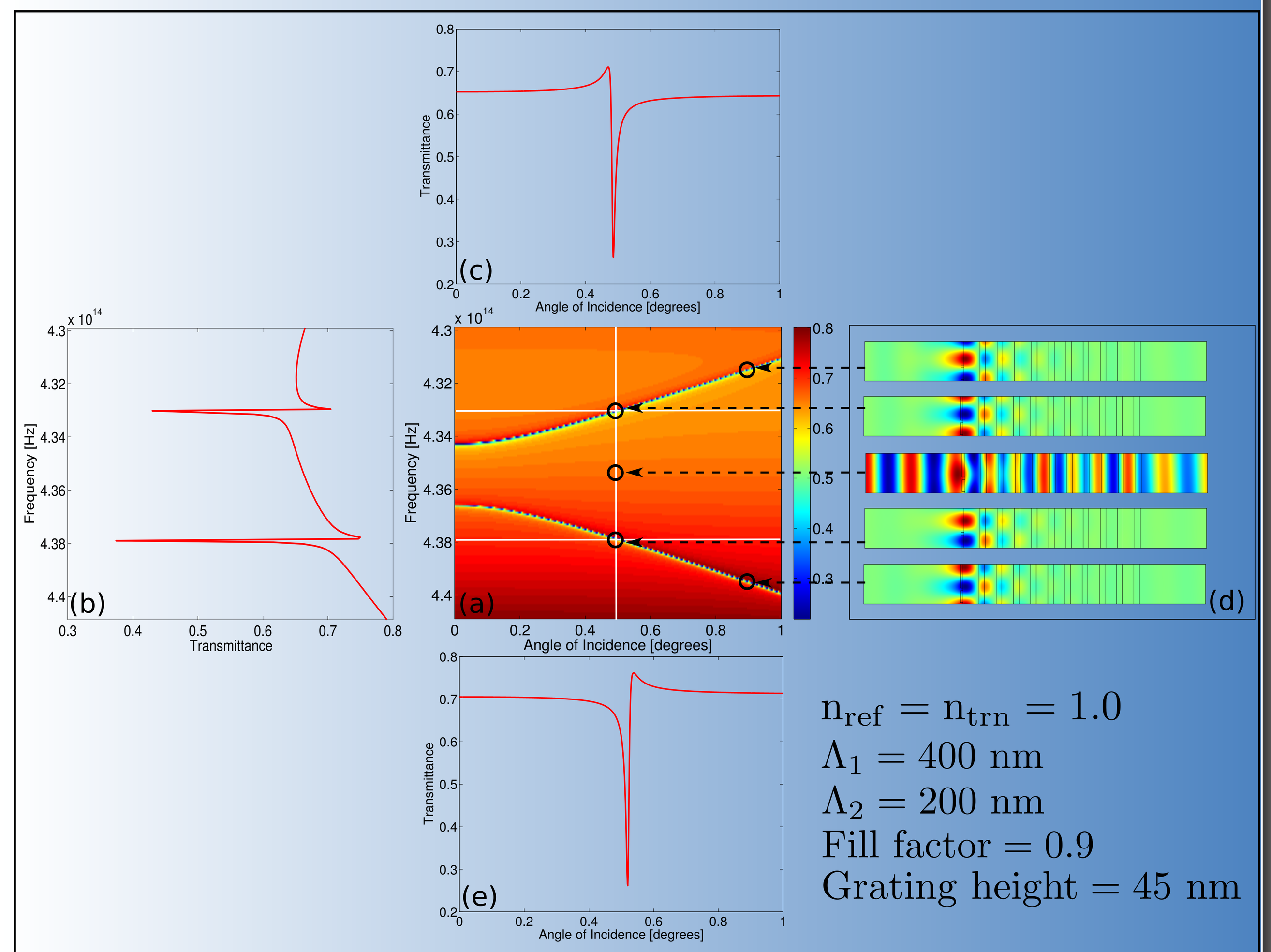

Figure 4.

- (a) Transmittance of the TiO_2-SiO_2 multilayer with two different grating periods as a function of frequency and incidence angle. Two distinct BSW modes are observed because of the presence of two grating periods.

- (b) Transmittance as a function of frequency for the incidence angle of 0.5 degrees (solid white vertical line in Figure 3(a)). Two sharp and narrow tranmission dips at different frequencies.

- (c) , (e) Transmittance as a function of incidence angle at two different frequencies. (c) and (e) are cross-sections across the upper and lower solid white horizontal lines in Figure 3(a) respectively. For both the frequencies, the transmission dips are observed at the same incidence angle of 0.5 degrees.

- (d) Surface plots of BSW generation at different frequencies and incidence angles denoted by solid black circles in Figure 3(a). Difference between the non-BSW and BSW mode can be clearly seen.

Future Directions

- Study the effect of different parameters such as grating height, grating period, grating fill out factor, and number of TiO_2-SiO_2 bilayers on the BSW generation and its sensitivity.

- Optimize the design of the multilayer structure with grating using a global optimization technique such as Particle Swarm Optimization.

- Utilize the non-linear effect due to enhanced electric field at the surface for other applications.

References

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