DIFFRACTION-GRATING-BASED BLOCH SURFACE WAVE REFRACTIVE INDEX SENSORS

E.A. Kadomina[1,2], E.A. Bezus[1,2], L.L. Doskolovich[1,2]

[1]Image Processing Systems Institute – Branch of the Federal Scientific Research Centre "Crystallography and Photonics" of Russian Academy of Sciences, Samara, Russia
[2] Samara National Research University, Samara, Russia

Abstract. A planar optical sensor consisting of a diffraction grating and a one-dimensional photonic crystal based on Bloch surface wave excitation effect is proposed. The obtained results can find application in the design of novel on-chip refractive index sensors.

Keywords: photonic crystal, Bloch surface wave, diffraction grating, optical sensor, Maxwell's equations, rigorous coupled-wave analysis.

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Introduction

Nowadays, resonant optical sensors based on the excitation of surface electromagnetic waves (surface plasmon polaritons (SPP) or Bloch surface waves (BSW)) are widely used for refractive index measurement and for detection of various micro-objects. SPP-based sensors [1–3] have a significant drawback, namely, high absorption losses in metals leading to broadening of the SPP resonance, which limits the sensor performance. BSW-based sensors are free from this disadvantage because BSW can be supported by all-dielectric structures. Moreover, BSW can be either TM- or TE-polarized, which adds one more degree of freedom to the sensor design. Recently proposed BSW-based sensors [4–9] possess high sensitivity (the accuracy of the measurement of the refractive index exceeds 10^{-6}). In the existing works, BSW are excited in the Kretschmann configuration, which leads to a relatively large size of the sensor. A promising approach to miniaturizing the sensors consists in the utilization of grating-based BSW excitation configuration and is studied in the present work.

Geometry and parameters of the optical sensor

Fig. 1 shows the geometry of the investigated sensor. The structure comprises a diffraction grating with one-dimensional periodicity and a one-dimensional photonic crystal (PC). The PC consists of N periods (N pairs of plane-parallel layers with alternating thicknesses and dielectric permittivities). Let us consider an example with the following parameters: PC layer thicknesses $h_1 = 96$ nm and $h_2 = 140$ nm, dielectric permittivities $\varepsilon_1 = 4.51 + 1.7\cdot10^{-3}i$ (corresponds to TiO_2 at $\lambda_0 = 550$ nm) and $\varepsilon_2 = 2.05 + 6\cdot10^{-4}i$ (corresponds to SiO_2 at $\lambda_0 = 550$ nm). At the upper surface of the PC, an additional layer with the thickness h' and the dielectric permittivity ε' is located. In the considered example, we set $\varepsilon' = \varepsilon_1$ and $h' = h_1 + h_c$, where $h_c = -63.8$ nm. The studied structure is intended for the measurement of the refractive index of the superstrate (the medium over the PC with the unknown refractive index n_{sup}). The working refractive index range in the considered example is 1.33–1.34 (distilled water and weak NaCl solutions). At the lower surface of the PC, a one-dimensional diffraction grating with the period d_{gr}, ridge height h_{gr}, ridge width l_{gr} and dielectric permittivity ε_{gr} (in the present example, $\varepsilon_{gr} = \varepsilon_1$) is located. The values of the parameters d_{gr}, h_{gr}, l_{gr} are chosen so that BSW are excited by a prescribed diffraction order (orders) of the grating.

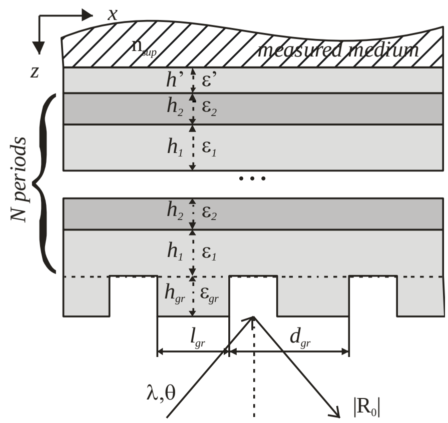

Fig. 1. Geometry of the investigated optical sensor consisting of a diffraction grating and a one-dimensional photonic crystal

The operating principle of the sensor consists in the measurement of the reflection coefficient at different (gradually varying) values of the incident angle or the incident wavelength. In the vicinity of the resonance that occurs at certain combinations of parameters (e.g., the refractive index of the superstrate and the angle of incidence), BSW is excited at the interface between the PC and the superstrate, which leads to a pronounced dip in the reflectance spectrum.

To evaluate the sensor performance, we use the following conventional figure of merit [6, 8]:

$$FoM = S_v \cdot D/W \,, \tag{1}$$

where S_v is the sensor sensitivity, D is the reflectance dip depth, and W is the dip FWHM (full width at half maximum). Depending on the varying parameter (angle of incidence θ or wavelength λ), the sensitivity is calculated using one of the following equations: $S_v = \partial\theta_{\min}/\partial n$ or $S_v = \partial\lambda_{\min}/\partial n$, where $\theta_{\min}$ and $\lambda_{\min}$ are the angular and spectral locations of the minimum, respectively. In order to compare the investigated structure with the conventional sensor configuration (Kretschmann geometry), a sensor comprising a prism made of BK7 optical glass instead of the diffraction grating was also simulated.

Let us note that the FoM values given below were obtained on the basis of a rigorous solution of the Maxwell's equations using the Fourier modal method [10, 11]. The derivation of the BSW dispersion relation and the conditions of BSW excitation by prescribed diffraction orders of a diffraction grating were described in detail in the previous works of the present authors [12, 13].

Performance of the optical sensor at varying angle of incidence

The sensing performance of the considered structure was investigated for the following superstrate media: double-distilled water and 1%, 2% and 3% NaCl solutions with the refractive indices equal to 1.3330, 1.3347, 1.3364, and 1.3381, respectively.

The values of the diffraction grating parameters $d_{gr} = 453.2$ nm, $h_{gr} = 563.7$ nm, $l_{gr} = 0.59 d_{gr}$ were found using an optimization procedure from the condition of BSW excitation by the first diffraction order at the incidence angle of 10º and the superstrate refractive index of 1.335.

Fig. 2 shows the absolute value of the reflection coefficient vs. the incidence angle for the four measured media. According to Fig. 2, the resonance (the reflection dip) is present for all considered media. Let us note that the angular position of the reflectance dip changes continuously and monotonically with the change in the refractive index of the measured medium. The performance of the grating-based sensor and the sensor based on the Kretschmann geometry is compared in Table 1. It follows from Table 1 that the FoM values for the sensor with a diffraction grating are slightly lower than the values for the sensor based on the Kretschmann configuration. At the same time, these values are significantly (by almost 5 times) greater than the theoretical limit for SPP-based sensors with a gold film ($FoM = 108\text{RIU}^{-1}$) [1].

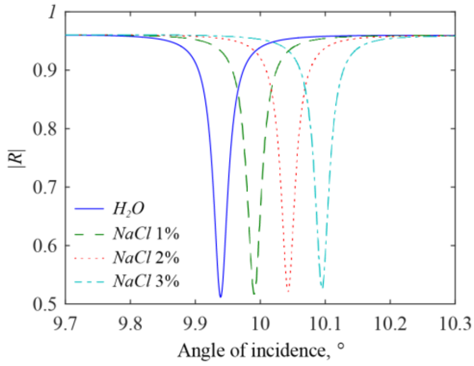

Fig. 2. The absolute value of the complex reflection coefficient vs. angle of incidence for different superstrate media

Table 1. Comparison of the performance of the grating-based sensor and the sensor based on the Kretschmann configuration in the case of varying angle of incidence.

	ddH_2O	*NaCl* 1%	*NaCl* 2 %	*NaCl* 3%
Sensor based on the Kretschmann geometry				
$S_v, ° / RIU$	48.46	48.85	49.24	49.05
$W \times 10^{-2}, °$	3.82	3.81	3.80	3.79
D	0.519	0.518	0.516	0.514
FoM, RIU^{-1}	659	664	669	665
Sensor with a diffraction grating				
$S_v, ° / RIU$	30.46	30.61	30.76	30.68
$W \times 10^{-3}, °$	2.71	2.69	2.67	2.65
D	0.449	0.444	0.440	0.435
FoM, RIU^{-1}	504	505	506	504

Performance of the optical sensor at varying wavelength

Let us now study the performance of the considered sensors in the case of varying wavelength.

As in the previous case, the grating parameters $d_{gr} = 396.8$ nm, $h_{gr} = 805.5$ nm, $l_{gr} = 0.72 d_{gr}$ were found using an optimization procedure. In the present example, two counter-propagating BSW were excited by $\pm 1^{\text{st}}$ diffraction orders at normal incidence of the wave with $\lambda_0 = 550$ nm at $n_{\text{sup}} = 1.335$.

Similarly to Fig. 2, it is evident from Fig. 3 that the reflection dip is present for all measured media. The comparison of the proposed sensor with the sensor in the Kretschmann configuration is given in Table 2. It follows from Table 2 that in the case of varying wavelength, the grating-based sensor provides better average FoM value.

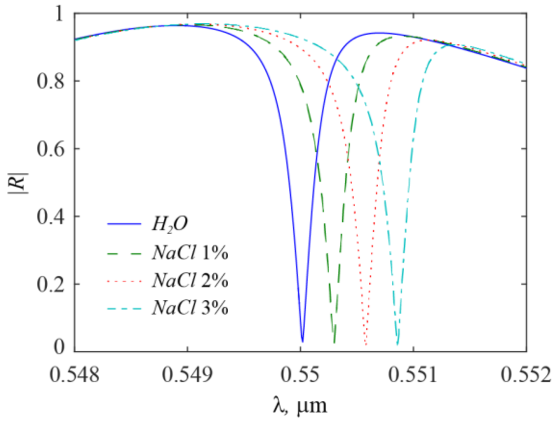

Fig. 3. The absolute value of the complex reflection coefficient vs. wavelength for different superstrate media

Table 2. Comparison of the performance of the grating-based sensor and the sensor based on the Kretschmann configuration in the case of varying wavelength.

	ddH_2O	***NaCl* 1%**	***NaCl* 2 %**	***NaCl* 3%**
Sensor based on the Kretschmann geometry				
S_v, nm/RIU	773.5	786.9	801.0	794.0
W, nm	0.610	0.610	0.612	0.613
D	0.502	0.513	0.526	0.540
$FoM \times 10^3$, RIU^{-1}	636	662	689	699
Sensor with a diffraction grating				
S_v, nm/RIU	163.9	165.2	166.5	165.8
W, nm	0.218	0.218	0.219	0.228
D	0.939	0.954	0.968	0.956
$FoM \times 10^3$, RIU^{-1}	707	722	735	695

Conclusion

In the present work, a planar configuration of an optical refractive index sensor was proposed and numerically investigated. The sensor contains a diffraction grating with one-dimensional periodicity and a one-dimensional photonic crystal. The working principle of the sensor is based on the excitation of Bloch surface waves. As a varying parameter, the angle of incidence or the wavelength can be used. The proposed sensor is compared with the conventional sensor based on the Kretschmann configuration in the case of four measured media: double-distilled water and 1%, 2% and 3% NaCl solutions. It is shown that two sensor configurations have comparable performance, which significantly exceeds the theoretical limit for SPP-based sensors with gold films. The obtained results may find application in the design of novel on-chip refractive index sensors.

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