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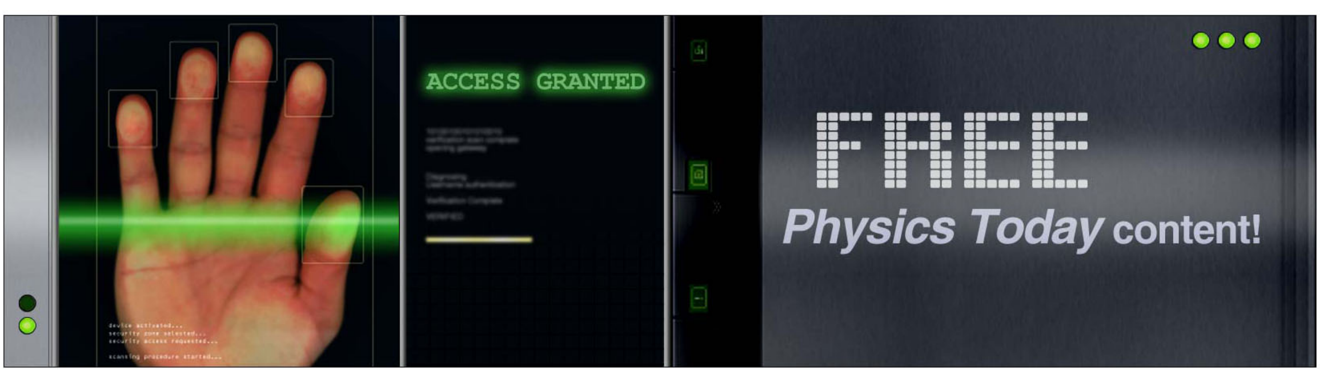

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Phase properties of Bloch surface waves and their sensing applications

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We study the phase properties of Bloch surface waves (BSWs) on truncated one-dimensional photonic crystals and find an abrupt change of the phase induced by BSWs. The phase of the BSW device shows a prominent response to the refractive index changes of the environment under resonance conditions. Furthermore, we demonstrate that the phase sensitivity of the BSW device is higher by nearly 1 order of magnitude than its amplitude sensitivity in terms of the figure of merit. This means that phase detection can be utilized to enhance the sensitivity of the BSW devices. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4816810]

Phase in optical systems plays a crucial role in holographic optics[1] and phase modulators.[2] Both phase and amplitude of electromagnetic field carry information about the medium in which light propagates. Therefore, besides detecting the amplitude parameters, i.e., transmittance and reflectance, obtaining the phase information in optical systems is equally important.

Phase detection has been applied to the surface plasmon resonance (SPR) sensing technique.[3–5] The SPR sensors based on phase detection has higher sensitivity[6] and is more suitable for SPR imaging[7] when compared to the amplitude based sensors.

Surface electromagnetic waves supported by one-dimensional photonic crystals (1D PCs) with truncated surfaces exhibit similar behavior to SPR.[8,9] The surface waves are called Bloch surface waves (BSWs) that propagate along the interface between the 1D PC and the ambient medium.[10] BSWs are tightly confined to the surface, which leads to a surface field enhancement that makes possible a great variety of applications such as fluorescence emission enhancement[11] and surface enhanced Raman scattering.[12]

BSWs cannot be excited directly in air because the wave vector of BSWs at each frequency lies beyond the light line. The incident light is coupled into the surface modes of photonic crystals only when the phase-matching condition is satisfied, which can be achieved in the Kretschmann or Otto configuration.[13] A dip in the reflection spectrum is produced when BSWs are excited at the surface and can be directly detected by measuring the amplitude of the reflection coefficients. Many BSW sensors based on the reflectivity detection in the angular or wavelength spectrum have been demonstrated.[14–18]

In general, the phase of an optical system manifests the step-like jump when the amplitude parameter of the system drops sharply.[19] Accordingly we can expect that the phase undergoes an abrupt change when BSWs are excited. In this letter, we find the expected abrupt phase change induced by the BSW resonance in the 1D PC. The phase of the BSW device shows a prominent response to the refractive index changes of the environment under resonance conditions, which makes it possible to develop a BSW sensor based on phase detection with high sensitivity.

Our experimental setup utilized for characterizing BSWs in the 1D PC is a rotating polarizer-analyzer (RPA) scanning ellipsometer[20] with the Kretschmann configuration as shown in Fig. 1. Here, we design a 1D PC device denoted by prism/$(HL)^4H'$/air, where H is TiO_2 with a thickness $d_H = 120$ nm, L is SiO_2 with $d_L = 178$ nm, H′ is TiO_2 with $d_{H'} = 64.3$ nm as the termination layer, and 4 is the periodic number of 1D PC. TiO_2/SiO_2 multilayers are alternatively deposited by ion-assisted e-beam evaporation on a hemicylindrical prism made of BK7 glass. The refractive indices of TiO_2 and SiO_2 are, respectively, 2.167 and 1.428 at our target wavelength of 420 nm. Their extinction coefficients are set at 3.3×10^{-3} and 2×10^{-4}, respectively, taking into account the intrinsic material loss and the scattering loss from the interfacial roughness.

In this measurement scheme (see Fig. 1), the incident angle θ is set by a computer-controlled goniometer on which the 1D PC device is mounted. The liquid cell in contact with the last layer of the device can be filled with different aqueous solutions or air. The continuum light source in the experimental setup is provided by a Xenon lamp. A monochromator with a 1200 line/mm grating produces the quasi-monochromatic light. The photomultiplier tube (PMT) with high sensitivity is used as the detector in the ellipsometer. The fixed polarizer P_0 is perpendicular to the incident plane. The linear polarizer and the linear analyzer rotate synchronously at the ratio of 1:2. Ellipsometric parameters Δ and ψ can be obtained, which are defined by the complex-valued ratio ρ of the complex reflection coefficients r_p and r_s for the light parallel (p) and perpendicular (s) to the incident plane as follows:

$$\rho = \frac{r_p}{r_s} = \tan\psi \exp(i\Delta), \quad (1)$$

where ψ represents the angle obtained from the amplitude ratio between the reflected p- and s-polarizations, while Δ

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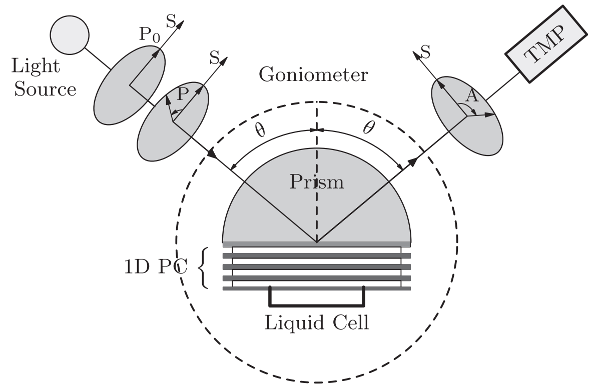

FIG. 1. The BSW device with the 1D PC composed of periodic SiO_2 and TiO_2 alternating multilayers deposited on BK7 prism; the RPA ellipsometer for characterizing BSWs with the Kretschmann configuration.

expresses the phase difference between the reflected p- and s-polarizations. Because a RPA ellipsometer only provides cosΔ value, the sign of Δ is uncertain. Both theoretical and experimental Δ values are confined to the range of 0-180°. ϕ_p and ϕ_s, the phase of p- and s-polarized reflected light, are obtained from their complex reflection coefficients which can be written in the form

$$r_p = |r_p|\exp(i\phi_p),\\ r_s = |r_s|\exp(i\phi_s). \tag{2}$$

Reflectivity ($R = |r|^2$), reflection phase, and ellipsometric parameters of the 1D PC device can be theoretically calculated by Fresnel's equations.[21]

Fig. 2(a) shows the numerically calculated reflectivity and the corresponding phase of p- and s-polarized light for the 1D PC device in the wavelength range of 400–440 nm at the incident angle of 70°. When the phase-matching condition is achieved, the dip induced by BSWs appears in the reflectivity spectrum of the p-polarization light at the wavelength of 420 nm. Furthermore, the maximal phase change is expected to occur at the minimum of the amplitude response.[19,22] Indeed, for the p-polarized component, the sharp jump of phase at the BSW resonance is confirmed in our simulation as shown in Fig. 2(a). In contrast, for the s-polarized component, both the reflectivity and the phase are almost constant in the vicinity of the resonance since BSWs cannot be excited.

Fig. 2(b) shows the plots of the numerically calculated and experimentally determined ellipsometric parameters as a function of wavelength at the incident angle of 70°. The s-component cannot excite BSWs on our 1D PC device within the wavelength range of 400–440 nm, so that the reflection coefficient $|r_s|$ is approximately constant. According to $\psi = \arctan(|r_p|/|r_s|)$, the ellipsometric parameter ψ has characteristics of the p-component reflectivity when BSWs are excited. Therefore, a dip of the ψ plot appears where the ordinary BSW dip is observed in the reflectivity spectrum R_p.[8] As described earlier, the phase of the p-component changes rapidly as the excitation of BSWs occurs, so that the light reflected from the BSW device becomes elliptically polarized. The ellipticity and orientation of the polarization ellipse change rapidly, which is induced by BSWs. Correspondingly, a sharp jump-like change appears in the Δ spectrum as shown in Fig. 2(b). The behavior of the phase of the light reflection from the BSW device is analogous to that from the SPR device. This means it will be possible to develop BSW sensors based on phase detection.

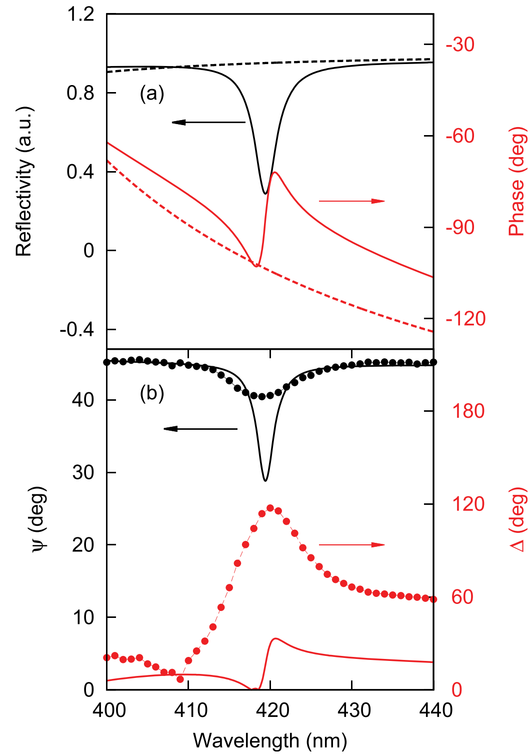

FIG. 2. (a) Calculated reflectivity and corresponding phase of the p- and s-polarizations for the BSW device at the incident angle of 70°. Black solid line corresponds to R_p and black dashed line R_s. Red solid line corresponds to ϕ_p and red dashed line ϕ_s. (b) Comparison of the calculated (solid lines) and measured (dotted lines) ellipsometric parameters, ψ (black) and Δ (red), as a function of wavelength at the 70° angle.

Although there are agreements between the calculated and the measured ellipsometric parameters, we also note that the calculated BSW resonance is narrower and deeper than that observed in the experiment. There are mainly two following reasons for these discrepancies. First, the angular-spread of the incident light in our ellipsometer is about 2.4 mrad, which can broaden the resonance width.[23] Second, the bandwidth of the quasi-monochromatic light from the monochromator is about 1.7 nm. The quasi-monochromatic light also can broaden the resonance width.

To study the response of our BSW device to the refractive index variant of the environment, we use pure water (with ethanol concentrations of 0% v/v) and the water-ethanol mixture with ethanol concentration of 20% v/v as the cladding. Fig. 3(a) shows the amplitude and phase responses of the described BSW device. We find that the BSW resonance position of the described device shifts from 461 nm to 468 nm when the flow cell is filled, respectively, with pure water and the water-ethanol mixture. There is an estimated refractive index difference $\delta n \approx 1.11 \times 10^{-2}$ refractive index unit (RIU) between the pure water and the mixture (20% v/v).[24] Our measured sensitivity is about 631 nm/RIU at the vicinity of 460 nm. The result is very close to that of Farmer's study.[16] Here, we emphasize that the phase produces prominent changes owing to the refractive index variant of the environment as shown in Fig. 3(a).

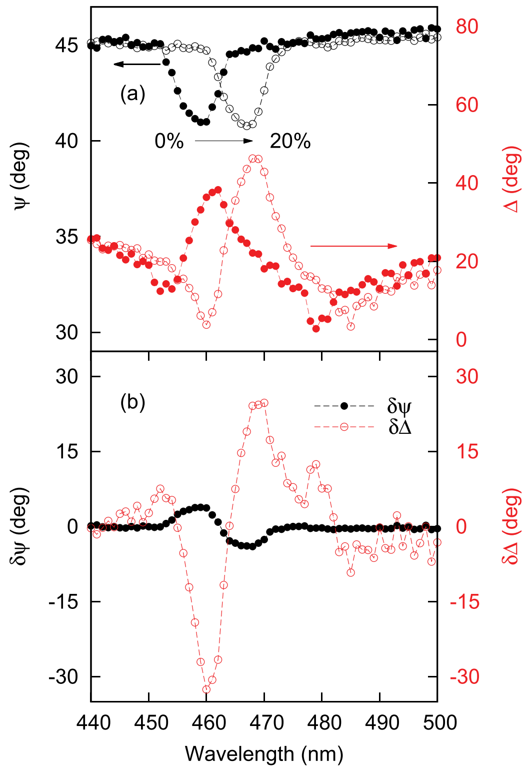

FIG. 3. (a) Shift of the curves of ψ (black) and Δ (red) as the flow cell is filled with pure water (close circle) and the water-ethanol mixture with ethanol concentrations of 20% v/v (open circle). (b) The difference of the amplitude and phase, $\delta\psi$ and $\delta\Delta$, for BSWs.

To estimate the performance of the sensors, the figure of merit (FOM)[25] is introduced, which can be defined as

$$\mathrm{FOM} = \frac{\delta\Delta}{\delta\psi}, \quad (3)$$

where $\delta\psi$ and $\delta\Delta$ are the differences of the amplitude and the phase, respectively. We plot $\delta\psi$ and $\delta\Delta$ in the wavelength region of BSWs for pure water and the water-ethanol mixture as shown in Fig. 3(b). The value of FOM is about 8 at the 460 nm wavelength. This shows that the phase (Δ) sensitivity of the BSW device is higher by nearly 1 order of magnitude than the amplitude (ψ) sensitivity of the device, which is similar to the SPR device.[26] Therefore, phase detection can be utilized to enhance the sensitivity of the BSW device.

In summary, the phase properties of Bloch surface waves in 1D PCs have been studied. It is theoretically and experimentally shown that the phase of the reflected light from the studied BSW device changes rapidly as the excitation of BSWs occurs. The behavior of the BSW phase makes it possible to develop BSW sensors based on phase detection. Furthermore, it is experimentally demonstrated that the phase sensitivity of the BSW device is higher by nearly 1 order of magnitude than its amplitude sensitivity.

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