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Optical Tamm mode based refractometer in all-dielectric configuration

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Abstract

Optical Tamm (OT) modes formed at the interface of distributed-Bragg reflector (DBR) and low-index dielectric material, exhibit strong dispersive features at optical frequencies which gives rise to the possibility of designing refractometer with improved sensitivity. Using this idea, we design a TiO_2/SiO_2 based DBR configuration for sensing refractive-index changes around 1.33 using spectral-interrogation as well as angular-interrogation method. Dispersion characteristics of OT modes in the DBR configuration are tailored to obtain spectral sensitivity ~1200 nm/RIU and angular sensitivity ~40°/RIU for both transverse-electric (TE) and transverse-magnetic (TM) polarizations. We also show that the sensitivity could be substantially tuned over a wide range by appropriately choosing the thicknesses of DBR constituent layer. An all-dielectric DBR configuration gives rise to the possibility of realizing refractometer in any desired spectral region by linearly translating the dispersive behavior of photonic bandgap (PBG) guided OT modes.

Keywords: Photonic bandgap; Surface mode; Refractive index; Dispersion

1. Introduction

Biochemical sensing using optical surface modes such as surface-plasmon-polaritons (SPP), surface-enhanced Raman scattering (SERS) etc. have gained overwhelming prominence over the last two decades due to design simplicity and label-free detection mechanism [1,2]. The obvious advantage is derived from the mode-field distribution of surface modes which are characterized by a decaying field envelope in the constituent layers (one of them being sensing medium) and field-maximum at the interface. Therefore, the changes taking place at the surface could be sensed by monitoring the changes in surface mode-field and quantified in terms of transmission or reflection spectra. Here, it is primarily determined by the dispersion characteristics of surface modes which is a function of material dispersions of constituents as well as the dispersion due to surface guidance mechanism. Since, in general, the interface is formed by two homogeneous semi-infinite media on either side, the possibility to tailor the dispersion by adopting the second route is impractical. Consequently, the emphasis is mainly laid on improving material dispersive features to enhance the sensitivity of such sensors [2,3]. In this

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context, surface modes formed at the interface of a homogeneous medium and a periodically-stratified medium, also called optical Tamm (OT) mode [4,5], have been rarely investigated from the perspective of sensing refractive index changes in homogeneous medium [6,7]. Photonic bandgap (PBG) based guidance mechanism for OT modes could provide the flexibility to tailor the surface-mode dispersion characteristics by suitably designing the periodically stratified medium and hence, bring appreciable control over the sensor performance parameters such as sensitivity and detection accuracy. Previously, Tamm-plasmon-polariton (TPP) modes have been investigated for developing compact slow-light devices [8], enhancing $\chi^{(3)}$ nonlinearity for devising low threshold bistable optical switching [9], efficient third harmonic generation [10], realizing tunable plasmon polaritons [11] and many more [12,13]. Here, we present a nano-micro fabrication compatible, widely-employed TiO_2/SiO_2 based distributed-Bragg-reflector (DBR) configuration for realizing an OT mode refractive index sensor which exhibit high sensitivity to changes in analyte index. We show that the possibility to control the mode-field penetration of OT mode in analyte region by suitably designing the DBR geometry facilitates optimum sensor characteristics. Due to all-dielectric configuration of OT mode sensor, the mode-field attenuation is negligible as compared to plasmonic sensors and hence, they are expected to have large sustainable electromagnetic (EM) field at the interface which is expected to improve the sensitivity as well as signal-to-noise ratio for the configuration. In addition, the PBG guidance mechanism also gives flexibility to tailor OT mode dispersion so as to achieve improved detection accuracy.

It is well-known that the SPP modes, are non-radiating and lie below the light-line of medium constituting the interface. Therefore, specially designed geometries based on attenuated-total-reflection (ATR) and grating couplers are used for SPP mode excitation [14]. In case of ATR based excitation, light is incident on the surface using high-index prism so as to compensate for the wavevector mismatch [15]. On the other hand, the periodic modulation of refractive index in grating-coupler facilitates phase-matching between waveguide modes to the SPP mode. Due to the bandgap-based guidance mechanism, OT modes lie above the light-line of medium constituting the interface and hence, efficient excitation could be carried out using prisms (ATR configuration) with refractive index slightly greater than the low-index layer of DBR geometry [16,17]. Additionally, the grating couplers are also an viable option which is yet to be explored in the context of OT mode excitation.

2. DBR designing

We consider a geometry shown in Fig. 1(a) where the boundary at $x = 0$ is shared by a semi-infinite TiO_2/SiO_2 based DBR-section with an analyte layer characterized by refractive index n_a. The refractive index of TiO_2 is n_1 and that of SiO_2 is n_2 with thicknesses d_1 and d_2, respectively. The periodicity (Λ) is given by $\Lambda = d_1 + d_2$. The refractive index profile (RIP) of

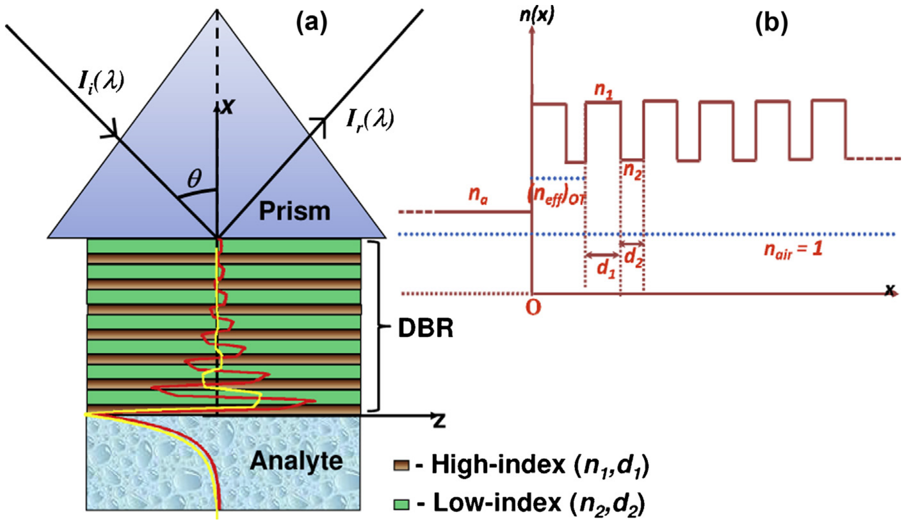

Fig. 1. (a) Schematic of TiO_2/SiO_2 DBR based sensing configuration using OT modes; Propagation direction: z-axis; OT mode-field distribution superimposed over the structure (Yellow-TE, Red-TM). (b) Refractive index profile (RIP) of planar geometry in Fig. 1(a) where the location of n_{eff} for the OT mode with respect to constituent material refractive indices is shown.